

AD 665328

VALIDATION OF DESIGN THEORY FOR
AIRCRAFT ARRESTING-GEAR CABLE

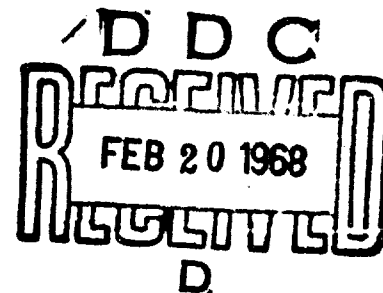
FINAL REPORT

January 19, 1968

by

Philip T. Gibson, Graham H. Alexander, and Hobart A. Cress

Prepared under Contract NOw 65-0503-c for
the Naval Air Systems Command, Department
of the Navy, by Battelle Memorial Institute,
Columbus Laboratories, 505 King Avenue,
Columbus, Ohio 43201



COPIES OF THIS REPORT MAY BE OBTAINED DIRECTLY
FROM THE DEFENSE DOCUMENTATION CENTER, CAMERON
STATION, ALEXANDRIA, VIRGINIA

DISTRIBUTION OF THIS REPORT IS UNLIMITED

84

FINAL REPORT

on

VALIDATION OF DESIGN THEORY FOR
AIRCRAFT ARRESTING-GEAR CABLE

to

NAVAL AIR SYSTEMS COMMAND
DEPARTMENT OF THE NAVY
(Contract No. NOW 65-050342)

January 19, 1968

by

Philip T. Gibson, Graham H. Alexander, and Hobart A. Cress

BATTELLE MEMORIAL INSTITUTE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION AND SUMMARY.	1
CONCLUSIONS.	2
ARRESTING CABLE DESIGN CONSIDERATIONS	3
Tensile and Bending Stresses in Wires	4
Interstrand Contact Stresses	4
Stresses Resulting from Hook Impact	5
Abrasion	6
Corrosion	7
GENERAL WIRE-ROPE DESIGN VARIABLES	7
SELECTION OF IMPROVED ARRESTING CABLE	11
EXPERIMENTAL EVALUATION OF SELECTED WIRE-ROPE CONSTRUCTIONS	12
Tests of Wire-Rope Torsion, Elastic Modulus and Ultimate Strength	14
Testing Construction E	15
Testing Constructions B, C, D, and F	20
Tests of Wire-Rope Flexibility	21
Transverse-Impact Tests	23
APPENDIX A	
WIRE-ROPE CONSTRUCTIONS SELECTED FOR EXPERIMENTAL EVALUATION	A-1
APPENDIX B	
WIRE-ROPE PHYSICAL PROPERTIES.	B-1
APPENDIX C	
WIRE-ROPE TORQUE CHARACTERISTICS	C-1
APPENDIX D	
WIRE-ROPE LOAD-ELONGATION CURVES.	D-1

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
APPENDIX E	
MEASURED WIRE-ROPE CHARACTERISTICS.	E-1

APPENDIX F	
TRANSVERSE-IMPACT VELOCITIES	F-1

APPENDIX G	
PHOTOGRAPHS OF WIRE-ROPE DAMAGE RESULTING FROM TRANSVERSE-IMPACT TESTS	G-1

APPENDIX H	
RESULTS OF TRANSVERSE-IMPACT TESTS	H-1

LIST OF TABLES

Table B-1. Wire-Rope Physical Properties	B-1
Table E-1. Measured Wire-Rope Characteristics	E-1
Table F-1. Transverse-Impact Velocities	F-1
Table H-1. Results of Transverse-Impact Tests	H-1

LIST OF FIGURES

Figure 1. Anchor End of Rope Specimen in Tensile Machine	16
Figure 2. Loading End of Rope Specimen in Tensile Machine	16
Figure 3. Experimental Aircraft-Arresting Cable (Construction E)	17
Figure 4. Cross Section of Cable Specimen (Construction E)	18
Figure 5. Apparatus Used to Measure Wire-Rope Flexibility.	22
Figure 6. Apparatus Used For Transverse-Impact Tests	24
Figure 7. Cannon With Hook Point Ready For Firing	24

LIST OF FIGURES
(Continued)

	<u>Page</u>
Figure 8. Positions of Hook Point and Wire-Rope Specimen at Instant of Impact.	25
Figure 9. Weights Used to Decelerate Hook	25
Figure 10. Rope Motion Following Impact	25
Figure A-1. Construction A, 1-3/8-Inch, 6 x 30, Lang-Lay, Flattened-Strand Rope.	A-1
Figure A-2. Construction B, 1-3/8-Inch, 6 x 10/12/Brangle, Lang- Lay, Flattened-Strand Rope.	A-2
Figure A-3. Construction C, 1-3/8-Inch, 6 x 8/12/Brangle, Lang- Lay, Flattened-Strand Rope.	A-3
Figure A-4. Construction D, 1-3/8-Inch, 6 x 7/Brangle, Lang-Lay, Flattened-Strand Rope.	A-4
Figure A-5. Construction E, 1-3/8-Inch, 6 x 36 Half Lock, Lang- Lay, Flattened-Strand Rope.	A-5
Figure A-6. Construction F, 1-3/8-Inch, 6 x 31, Lang-Lay, Round-Strand Rope	A-6
Figure C-1. Wire-Rope Torque Characteristics	C-1
Figure D-1. Load-Elongation Curves For Wire-Rope Construction A .	D-1
Figure D-2. Load-Elongation Curves For Wire-Rope Construction B, Specimen 1	D-2
Figure D-3. Load-Elongation Curves For Wire-Rope Construction B, Specimen 2	D-3
Figure D-4. Load-Elongation Curves For Wire-Rope Construction C, Specimen 1	D-4
Figure D-5. Load-Elongation Curves For Wire-Rope Construction C, Specimen 2	D-5
Figure D-6. Load-Elongation Curves For Wire-Rope Construction D, Specimen 1	D-6

LIST OF FIGURES (Continued)

	<u>Page</u>
Figure D-7. Load-Elongation Curves For Wire-Rope Construction D, Specimen 2.	D-7
Figure D-8. Load-Elongation Curves For Wire-Rope Construction E, Specimen 1.	D-8
Figure D-9. Load-Elongation Curves For Wire-Rope Construction E, Specimen 2.	D-9
Figure D-10. Load-Elongation Curves For Wire-Rope Construction F, Specimen 1.	D-10
Figure D-11. Load-Elongation Curves For Wire-Rope Construction F, Specimen 2.	D-11
Figure G-1. Impact Area of Rope Constructions A, B, and C	G-1
Figure G-2. Impact Kink of Rope Constructions A, B, and C	G-2
Figure G-3. Impact Area of Rope Constructions D, E, and F	G-3
Figure G-4. Impact Kink of Rope Constructions D, E, and F	G-4
Figure G-5. Rope-Core Damage Due to Impact Tests	G-5
Figure G-6. Impact Area of Strands of Rope Construction A.	G-6
Figure G-7. Reverse Side of Strands of Rope Construction A	G-7
Figure G-8. Impact Area of Strands of Rope Construction B	G-8
Figure G-9. Reverse Side of Strands of Rope Construction B	G-9
Figure G-10. Impact Area of Strands of Rope Construction C	G-10
Figure G-11. Reverse Side of Strands of Rope Construction C	G-11
Figure G-12. Impact Area of Strands of Rope Construction D	G-12
Figure G-13. Reverse Side of Strands of Rope Construction D	G-13
Figure G-14. Impact Area of Strands of Rope Construction E	G-14
Figure G-15. Reverse Side of Strands of Rope Construction E	G-15

LIST OF FIGURES
(Continued)

	<u>Page</u>
Figure G-16. Impact Area of Strands of Rope Construction F. . . .	G-16
Figure G-17. Reverse Side of Strands of Rope Construction F	G-17

VALIDATION OF DESIGN THEORY FOR AIRCRAFT ARRESTING-GEAR CABLE

by

Philip T. Gibson, Graham H. Alexander, and Hobart A. Cress

INTRODUCTION AND SUMMARY

The work discussed in this report is the outgrowth of an earlier project entitled "Analytical Study of Aircraft Arresting-Gear Cable Design". The wire-rope design theory developed during this first study, together with information obtained from a number of wire-rope manufacturers, was used to select five different wire-rope constructions for evaluation as improved aircraft arresting cable. One of these ropes is an experimental construction designed at Battelle. Samples of these ropes were purchased for testing.

The five wire ropes selected for evaluation included four flattened-strand and one round-strand construction. The standard rope design presently in use for deck pendants was used as a basis of comparison for all tests. These six rope constructions are described in Appendix A.

These five new wire-rope constructions plus the standard deck pendant rope were subjected to a series of tests to establish their suitability for use as arresting cable. This report discusses the selection of the new rope designs and the results of the testing program.

Tests on these wire ropes included evaluation of the following characteristics:

- (1) Ultimate strength
- (2) Elastic modulus
- (3) Torsion
- (4) Flexibility
- (5) Resistance to damage by transverse impact.

The tests of ultimate strength, elastic modulus, and torsion were conducted on the tensile machines in the test laboratories of the rope manufacturers. Rope tension, torsion, and elongation were measured with instrumentation designed and built at Battelle.

Tests of flexibility and resistance to transverse impact were conducted in Battelle's Columbus Laboratories. The transverse-impact tests required the design and construction of special apparatus utilizing an explosive-powered arresting hook. With this equipment, specimens of each wire-rope construction were impacted with the arresting hook at velocities equivalent to the landing speeds of aircraft on carriers. These impact tests proved to be the most satisfactory method of evaluating deck-pendant ropes in the laboratory.

CONCLUSIONS

The results of all tests must be considered simultaneously to obtain a true picture of the characteristics of each type construction. The tests of torsion and elastic modulus revealed no significant differences among the five new constructions selected for evaluation. While the elastic moduli were higher and the developed torques lower for these ropes than for the standard deck-pendant rope, these parameters may be changed within limits by altering the rope lay.

Notable differences in the characteristics of the test specimens became obvious during the tests of ultimate strength and flexibility. Rope Construction E, the experimental arresting cable fabricated with half-lock and round wires, proved to have both very high breaking strength and superior flexibility. The increased strength is attributable to the large metallic area of this design, and the flexibility results from the use of a large number of relatively small diameter wires in each strand. Two other rope constructions also proved to have somewhat better flexibility than the standard deck-pendant rope.

The transverse impact tests revealed that the constructions with the largest number of wires and good flexibility (Constructions A, E, and F) displayed a small, permanent kink angle at the impact point. However, it was also found that the smallest diameter wires were the ones most severely damaged due to notching by contact with adjacent wires (Constructions C and F). Therefore, it appears that some care must be exercised in the design of an arresting cable to avoid extremely small diameter internal wires that may be easily damaged by transverse impact. Some compromise must be reached whereby the rope will be sufficiently flexible without being overly sensitive to impact damage.

Rope Constructions C and D were the least flexible and retained quite pronounced permanent deformation at the point of impact. However, the resistance of these ropes to damage by wire notching and external abrasion appears to be good.

One test result that is difficult to explain is the permanent kink angle retained by rope Construction B. This rope proved to be fairly flexible during the bending tests; however, it produced the largest kink angle of all specimens. This point will be investigated more fully during the future series of impact tests.

These tests also revealed the sensitivity of the different fiber cores to impact damage. The sisal core of the standard deck-pendant rope was by far the most severely damaged at the impact point. The polypropylene core of the experimental arresting cable was also heavily damaged. However, the nylon-fiber cores were essentially unharmed by the impact tests. From these tests, it appears that nylon may be a far superior core material; however, more testing will be required to fully evaluate this type of core. It may have other disadvantages that have not yet been identified. It is quite important for an arresting cable to have a core that does not become shredded or broken. Deterioration of the core allows the rope to distort and the strands to be smashed together. The result is premature wire distortion, notching, and failure.

The impact tests also indicated that the six-wire-over-fiber or six-wire-over-iron drawn strand may be a superior core for flattened strands. The 3 x 2 core used in the strands of the standard deck-pendant rope becomes severely notched during rope manufacture and, therefore, is susceptible to wire breakage due to tensile loads or impact. The drawn-strand cores resist impact damage quite well and have superior load carrying ability while providing good support for the other wires in the rope strands.

While these tests revealed several important characteristics of each rope design, more experimental work is being undertaken to fully identify the rope construction(s) most suitable for the deck-pendant application. This work is already in progress on an additional 1-year program. The experimental rope design developed by Battelle-Columbus has quite promising properties, and it is expected that an additional length of this rope will be purchased for additional testing.

ARRESTING-CABLE DESIGN CONSIDERATIONS

During an earlier project entitled "Analytical Study of Aircraft Arresting-Gear Cable Design", the important parameters governing the endurance of a wire rope were identified. (See the Battelle report of May 28, 1965). This first year's work included the following:

- (1) An analytical investigation of arresting-cable dynamics to determine the tension history in the cable during an arrestment
- (2) A study of the influence of wire-rope constructional variations on the peak tensile stress developed during aircraft arrestment
- (3) An analysis of the internal loads and stresses produced in an arresting cable by both tension and bending
- (4) An examination of deck-pendant failure modes
- (5) A discussion of arresting-cable design criteria.

The important wire-rope design considerations are repeated here for convenience.

Tensile and Bending Stresses in Wires

The first consideration in evaluating a wire-rope design is, of course, the magnitude of the tensile stresses developed in the wires. These stresses must remain within reasonable limits when the rope is subjected to its maximum service tension and bending.

For a rope under axial tension, the tensile stresses in the wires can be calculated if the wire cross-sectional areas, wire-lay angles, and strand-lay angle are known. It is found that for a given metallic cross section, the tensile stresses may be reduced by a decrease in the lay angles.

For a rope subjected to both tension and bending, the tensile stresses on the wires depend also on the radius of the bend and the magnitude of internal rope friction. During bending, the rope experiences relative motion between the strands and between the strands and the core. This relative motion between the rope components increases with decreasing bend radius. If no internal friction were present, the strands would move so as to evenly distribute their tensile loads. However, the internal friction retards this motion and results in unequal load distribution and increased tensile stresses on some wires. For this reason it is desirable for a wire rope to have ample internal lubrication.

It has been found that the core in a wire rope becomes notched by the wires pressing against it. In regular-lay rope, these notches are at an angle of approximately 35 degrees with the axis of the rope. In Lang-lay rope, this angle is reduced to nearly zero. As a result, the strands of the Lang-lay rope may move more easily along the core during bending, thereby providing more evenly distributed strand loads and lower tensile stresses on the wires.

Another consideration for the condition of bending is the "flexibility" of the rope. This "flexibility" is actually an indication of the bending stresses produced in the wires. The stiffer a rope is, the higher will be the bending stresses in wires for a given bend radius. For this reason, when relatively small-radius bends are necessary, it is desirable to construct the rope of strands consisting of many wires of small diameter rather than a few wires of large diameter.

Interstrand Contact Stresses

When a wire rope is subjected to loading, the individual strands are pressed against each other and the rope diameter decreases. This interstrand loading produces high stresses at the points of wire contact. If these stresses are large enough to produce local yielding, a notch forms in the wires and the resulting

stress concentration reduces the tensile strength of the wire. These interstrand contact stresses can be calculated using the Hertz theory and the rope geometry. To maintain maximum rope strength, it is desirable to reduce these stresses as much as possible.

For a rope under axial tension, it is possible to eliminate the interstrand contact stresses by providing a core that will support the strands sufficiently to keep them from touching each other. However, when a rope is subjected to bending or transverse impact, a simple core will not prevent contact between strands. It then becomes necessary to use other means to reduce the stresses produced by the existing contact force.

One method is to use a shaped core that will eliminate interwire contact by providing a layer of core material between the strands. It is also possible to use shaped wires (noncircular cross section) for the outer layers of the strands, thus providing area contact rather than point contact between touching wires.

If it is desirable to use a simple round core and round wires, the interstrand contact stresses may be reduced in the following ways:

- (1) By reducing the lay angle of the strands, the contact force, and thus the contact stress, between the strands is reduced.
- (2) By reducing the lay angle of the wires in the strands, the crossing angle of two contacting wires is made smaller and the contact stress is lessened.
- (3) By using larger wires in the outer layers of the strands, the effect of contact stresses is reduced.

Stresses Resulting From Hook Impact

The impact of the arresting hook on the deck pendant distorts the rope cross section and increases the interstrand contact forces. This aggravates the crossed-wire contact stress. In addition, there also exists the contact stress between the rope and the hook. The latter is affected very little by the lay angles or the characteristics of the rope core, but it may be reduced considerably by use of shaped wires, Lang lay, shaped strands, or a combination of these. The Lang lay and the shaped strands (e.g., flattened strands) both provide an increase in length of wire contact with the hook. The shaped wires provide area contact rather than line contact.

In addition to the compressive stresses produced in the region of hook impact, there is also a longitudinal tensile wave established, which travels along

the arresting cable away from the point of hook impact. For the case of perpendicular impact on a wire rope initially at zero strain, the value of this tensile stress is approximately

$$\sigma = \left(\frac{E\rho^2 V^4}{4g^2 A^2} \right)^{1/3},$$

where

E = the elastic modulus of the rope, lb/in.²

ρ = the rope density, lb/ft

V = the impact velocity, ft/sec

A = the rope metallic area, in.²

g = gravitational constant = 32.2 ft/sec.²

Thus, the dynamic tensile stress produced in the rope may be decreased by reducing either the elastic modulus or the weight of the rope.

Abrasion

The abrasion resistance of wire rope is an important factor determining the useful life of an arresting cable. High abrasion is experienced during aircraft arrestment when the cable slides across the face of the hook as a result of an off-center or oblique landing. The cable is also subjected to abrasion as it moves over the rough deck.

In general, for a cable of given diameter, it is desirable to present to the abrading surface as large a cable surface area as possible. This means that the wires should have a flattened shape exposed to the outer surface of the rope, and that the strands should have a flattened shape to provide a large number of wires for contact with the hook and deck. Also, low lay angles should be used in order that each wire on the surface of the rope will have the longest possible line of contact with the hook or deck and the tendency of the wires to spring away from the strand as they wear will be reduced. All of these factors tend to reduce the unit pressure during abrasion, the result being a decrease in the total depth of wear on the wires. Obviously, if the outer wires are large diameter, more metal can be lost before a complete wire breakage occurs.

Corrosion

Since aircraft arresting-gear cable is exposed to sea water, it is necessary for it to have good corrosion resistance. Any amount of corrosion that occurs causes stress concentrations that promote tensile failure of the wires. This corrosion problem can be reduced by applying a protective coating of zinc or aluminum to the wires prior to the final drawing operation. Of course, a corrosion-preventative lubricant should be used on all wire ropes.

GENERAL WIRE-ROPE DESIGN VARIABLES

With the above-mentioned design considerations in mind, letters were sent to wire-rope companies throughout the United States and Canada requesting comments on possible improved designs for arresting cable. As a result of the response to these letters, trips were taken to several wire-rope mills to determine the capabilities and limitations of existing rope-fabricating equipment. The companies visited included Bethlehem Steel Corporation, Jones and Laughlin Steel Corporation, United States Steel Corporation, and Wire Rope Industries of Canada, Limited.

These discussions revealed the many design variables that must be considered during the selection of a wire rope for use in aircraft arresting gear. These variables and their basic characteristics are as follows:

A. Basic Rope Construction

- (1) Single strand
- (2) Six strands over a core

B. Type of Strand for a Six-Strand Rope

- (1) Round strand
- (2) Flattened strand

C. Type of Rope Lay

- (1) Regular lay
- (2) Lang lay
- (3) Alternate lay

D. Type of Core for Flattened Strands

- (1) Single triangular wire



- (2) Three wires, flat lay (zero lay angle)



- (3) Six Wires, flat lay



- (4) Three wires plus three filler wires, flat lay



- (5) 3 x 2 strand



- (6) A strand of six wires over a fiber core and drawn to a triangular cross section



- (7) A strand of six wires over an iron core and drawn to a triangular cross section



E. Type of Rope Core

- (1) Sisal rope
- (2) Polypropylene rope
- (3) Nylon rope
- (4) Polyvinyl chloride (solid core)

- (5) Independent wire-rope core (IWRC)
- (6) "Unitlay" construction
- (7) Coiled spring

F. Shape of Wires Used

- (1) Round wires
- (2) Half-lock and round wires



- (3) Full-lock wires



G. Type of Wire Material

- (1) Steel
- (2) Plated steel
- (3) Stainless steel.

A single-strand construction has excellent abrasion and crushing resistance, but the flexibility is poor and the elastic modulus is high. It may also tend to birdcage upon the sudden release of a tensile load. A six-strand rope is much more flexible and has a lower elastic modulus. However, it is less resistant to abrasion and crushing. Multistrand ropes may also contain more or less than six strands if desired, but the six-strand construction is considered to offer the best compromise of desired rope characteristics.

A six-strand rope construction may contain either round strands or flattened strands which are usually triangular in cross section. The use of flattened strands provides a rope with greater abrasion resistance and a greater resistance to inter-strand wire notching. This is due to the increased bearing area on the outer surface of the rope and between the strands. Also, the tensile strength of the rope is higher due to a larger metallic cross section. However, a flattened strand rope is usually not as flexible as a round strand rope.

A rope may have its strands wrapped either in a right- or left-hand direction around the rope core. Similarly, the individual strands may have the wires wrapped in either direction. A regular-lay rope is one that has the strand lay (the direction the wires are wrapped on the strands) opposite the rope lay (the direction the strands are wrapped around the rope core). Whether a rope is

called right regular lay or left regular lay depends on the direction of the rope lay. A Lang-lay rope is one that has the strand lay and rope lay in the same direction. In an alternate-lay rope, opposite strand lays are used in adjacent strands.

A regular-lay rope has good flexibility and stability. When under a tensile load, it will not unlay or unwrap as readily as a Lang-lay rope. However, the abrasion resistance of this construction is rather poor. A Lang-lay rope may not be as stable (it may birdcage or kink more easily), but the abrasion resistance of this construction is superior to that of a regular-lay rope. The alternate-lay design is an attempt to obtain the desirable characteristics of both the regular- and Lang-lay constructions, but it is very difficult to fabricate and is not considered to be entirely satisfactory.

To fabricate flattened strands it is necessary to have some type of triangular core over which to lay the outer layer(s) of wire. Seven basic core designs are available from the various wire-rope manufacturers. These are shown earlier in this report.

Core Design D1 tends to break up quickly due to either a high tensile load or bending. Core Designs D2, D3, and D4 provide good flexibility, with the last two giving the best support for the outer layer(s) of wire on the strand. However, these three designs have a common disadvantage. The core wire that is the closest to the center of the rope after rope fabrication must be shorter than the other wires. This is true since it always remains the nearest to the axis of the rope. It has been found that unless extreme care is taken, this wire may tend to "pop out" of the strand during rope fabrication.

Core Design D5 is actually a small rope having three strands of two wires each. Its overall cross-sectional shape is triangular. This type of core is used widely, but it has the disadvantage of breaking up when subjected to either a crushing load or a high-tensile load.

Core Designs D6 and D7 are considered to be the best for the arresting-rope applications. Both provide good flexibility and good support for the outer strand wires. The length of lay of this type of core strand is rather short, which allows the the core to elongate with the strand without premature tensile failure. This type of core also is resistant to crushing loads or impact.

A number of different types of cores are available for wire-rope centers. In the past, the most common core was a rope made of vegetable fiber. At the present time, cores are also made of polypropylene or nylon fiber. Of the fiber cores, the latter two are considered to be the most desirable. A vegetable-fiber core is difficult to produce to the close size tolerances required for wire-rope fabrication. In addition, it may absorb moisture, thereby contributing to corrosive deterioration of the wire. Furthermore, a vegetable-fiber core cannot sustain high elongation or impact loading without being torn apart. The quality of the materials used for vegetable-fiber cores has been gradually deteriorating over the past few years.

Synthetic-fiber cores appear to hold great promise for the arresting-rope application. They provide good strand support, can be produced to very close size tolerances, resist failure due to impact, will return to their initial shape after deformation, and will not absorb moisture.

Wire ropes are also available with a second small wire rope for a core. This independent wire-rope core increases the rope's tensile strength and crushing resistance, but reduces its flexibility. Also, there is a substantial problem of wire notching between the strands and the core. This may cause the IWRC to be broken up into small pieces after repeated loading and bending.

A modification of this general type of rope is a construction having six outer strands and six inner strands closed in one operation over a core so that all strands intermesh. This provides an exceptionally strong rope with good crushing resistance but, again, the flexibility is rather low. The problem of wire notching between the inner and outer strands is kept to a minimum by having the direction of lay of the wires in the outer strands opposite that of the wires in the inner strands. This allows line contact between the wires of these adjacent strands.

Another interesting rope core is a tightly coiled spring made of wire having a square cross section. It is doubtful that such a core would be useful for arresting rope since it increases the mass of the rope without increasing the strength.

The majority of the ropes used today contain all round wires. An exception to this is the locked-coil track strands and hoisting ropes. Round wires have high strength, are easy to fabricate into rope, and are relatively inexpensive. Shaped wires, on the other hand, have a lower strength, are more difficult to fabricate into rope, are more expensive, and may be less resistant to bending fatigue. However, using either half-lock or full-lock wires on the outer surface of strands provides excellent resistance to abrasion and wire notching. In general, the larger the outer-strand wires, no matter what the shape, the greater the rope-abrasion resistance will be. At the same time, however, rope flexibility is reduced; therefore, some compromise is needed for any particular rope application.

Most ropes are made with bright steel wires. Good corrosion resistance and internal rope lubrication is obtained if the wires are zinc or aluminum plated. Stainless steel wires are also used in some ropes.

SELECTION OF IMPROVED ARRESTING CABLE

The wire-rope design theory developed at Battelle together with the information obtained from the wire-rope manufacturers was used to select five rope designs for experimental evaluation. The standard 6 x 30, flattened-strand rope presently used for deck pendants was the basis of comparison for all tests. This

construction is shown in Figure A-1 of Appendix A. The five new rope constructions selected for testing are shown in Figures A-2 through A-6.

Figures A-2, A-3, and A-4 show ropes with flattened-strand constructions similar to the existing deck-pendant rope. However, instead of 12 outer wires in each strand, these ropes have 10, 8, and 7 outer wires respectively. The resulting increase in the size of the outer wires provides increased abrasion and wire-notching resistance, although the rope flexibility is reduced. These ropes were purchased from Wire Rope Industries of Canada, Limited. Each has a nylon-rope core and is a standard catalog construction. The strands each have a "Brangle" core consisting of a six-wire-over-iron strand drawn to a triangular cross section. This type of strand core provides good strength, flexibility, impact resistance, and resistance to failure due to either high tensile loads or bending.

The rope design shown in Figure A-5 is a further attempt to obtain a flattened-strand construction that has improved resistance to abrasion and wire notching. In this case, shaped wires are used to provide a large bearing area on the outer surface of the rope and between the strands. Furthermore, this construction has improved flexibility due to the small wires used. This rope is an experimental construction designed at Battelle and fabricated by the United States Steel Corporation. It has a polypropylene core, and the strands have a six-wire-over-fiber drawn-strand core. Although there was some doubt in the wire-rope industry about the success of fabricating this rope construction, the final product exceeded our original expectations. This rope has excellent flexibility and a high breaking strength.

The rope design shown in Figure A-6, also manufactured by Wire Rope Industries of Canada, Limited, is very similar to existing purchase cable. However, it has only ten outer wires per strand instead of twelve, thereby allowing an increase in wire diameter. This rope has increased abrasion resistance, and the resistance to bending fatigue should be adequate for the purchase-cable application.

The physical properties of each of these rope constructions are listed in Table B-1 of Appendix B.

EXPERIMENTAL EVALUATION OF SELECTED WIRE-ROPE CONSTRUCTIONS

The six wire-rope constructions procured for experimental evaluation were tested to determine the following characteristics:

- (1) Ultimate strength
- (2) Elastic modulus

- (3) Torsion
- (4) Flexibility
- (5) Resistance to damage by transverse impact.

All tests on Construction A were conducted in the Battelle Laboratories. For Construction E, the tests of ultimate strength, elastic modulus, and torsion were conducted on the tensile machine at the New Haven, Connecticut, rope mill of the United States Steel Corporation. For Constructions B, C, D, and F, these same three tests were conducted on the tensile machine in the laboratories of Wire Rope Industries of Canada, Limited. All remaining tests on Constructions B through F were completed at Battelle.

Initially in this program, the plans for rope testing included measurement of the dynamic elastic modulus of each construction. This parameter is required for any mathematical analysis of arresting-cable dynamics (elastic wave and kink propagation and resulting cable tension). It is suspected that the cable elastic modulus under dynamic conditions may not be equal to the value measured under static conditions.

Investigations into this area revealed that this work has been conducted previously on both 1-inch and 1-3/8-inch arresting cable by the Propulsion Research Corporation (Report No. R-239, October 15, 1956). During these tests, a suspended cable was subjected to longitudinal impact loads on one end while under various pretension loads. Measurements were taken of the impact velocity, the magnitude of the dynamic stress wave, and the propagation velocity of the elastic wave.

The results of these tests were used in conjunction with the following equations (which ideally are correct only for homogeneous, isotropic, perfectly elastic systems):

$$E = \rho c^2 \quad (1)$$

$$E = \frac{1}{\rho} \left(\frac{\Delta \sigma}{V_0} \right)^2 \quad (2)$$

where

E = elastic modulus, lb/in.²

ρ = material density, lb/in.³

c = propagation velocity of elastic wave, in./sec

$\Delta \sigma$ = dynamic stress increment, lb/in.²

V_0 = impact velocity, in./sec

It was discovered that Equation (1) indicates a dynamic elastic modulus somewhat higher than the measured static elastic modulus while Equation (2) indicates a value somewhat lower. Further investigations indicated that another parameter, the effective dynamic density, must be considered to resolve this enigma.

Equations (1) and (2) were solved simultaneously to give

$$E_e = c \left(\frac{\Delta \sigma}{V_o} \right) \quad (3)$$

$$\rho_e = \frac{1}{c} \left(\frac{\Delta \sigma}{V_o} \right) \quad (4)$$

the "effective dynamic elastic modulus" and the "effective dynamic density".

It was evident from the Propulsion Research Report that considerable effort had been expended to obtain the experimental data. However, as the authors indicated, the results of this project were not entirely satisfactory. There was considerable data scatter, and the results presented for the 1-inch cable were significantly different than the results for the 1-3/8-inch cable. This is difficult to explain since the static elastic moduli for these two cables are essentially equal.

In view of the obvious difficulties encountered in the experimental determination of the dynamic elastic modulus of a wire rope together with the limited practical value of this parameter for purposes of developing an arresting cable with improved abrasion and wire-notching resistance, it was decided to substitute a transverse-impact test which would simulate an actual aircraft engagement. The details of the test apparatus and the experimental results are presented later in this report. This test proved to be quite valuable for deck-pendant evaluation.

Tests of Wire-Rope Torsion, Elastic Modulus, and Ultimate Strength

The military specifications for deck-pendant cable indicate a minimum required breaking strength of 188,000 pounds. A minimum breaking strength of 175,000 pounds is specified for the present purchase cable. All ropes procured for testing were designed to meet the 188,000-pound breaking strength, and tensile tests were conducted to verify this value.

Two additional, important parameters for arresting cables are the elastic modulus and the torque characteristics. The mathematical analysis of cable dynamics indicates that a low value of elastic modulus is desirable to reduce the magnitude of the dynamic tensile stress resulting from arresting-hook engagement. Furthermore, the torque characteristics of the deck pendant must be nearly the same as the torque characteristics of the purchase cable to prevent one rope from causing the other to unlay markedly under tensile loading.

For tests of these parameters, Battelle-built instrumentation was used to measure tension, torsion, and, with one exception, elongation of the specimens. Figures 1 and 2 show the test setup at Wire Rope Industries of Canada, Limited. The strain-gage load cell used to measure tension and torsion can be seen in Figure 2. The load was applied to each specimen by the three hydraulic cylinders shown in the upper right of this figure. Rope elongation was measured on a dial-indicator extensometer attached directly to each rope specimen over a 50-inch gage length.

The test setup used at the United States Steel rope mill was quite similar. However, in this case, the test machine was vertical rather than horizontal, and it included an extensometer with a 100-inch gage length.

Testing Construction E

The first rope available for testing was Construction E, the experimental arresting cable. Photographs of this rope are shown in Figures 3 and 4. Three specimens were prepared by the personnel at the United States Steel Plant. A standard open zinc socket was installed on both ends of each specimen to give a rope length of 14 feet \pm 1 inch as measured between the sockets.

Four test runs were made using cable Specimen 1. During each of the first three runs the load on the specimen was increased slowly to 110,000 pounds and then decreased slowly to zero. The torque developed in the cable is presented in Figure C-1 of Appendix C. The rope elongation under load is shown in Figure D-8 of Appendix D. All instrumentation was removed from the specimen for the fourth run so that the cable could be pulled to failure. The breaking strength of this specimen was 210,000 pounds. Failure occurred adjacent to the socket.

The testing procedure for cable Specimen 2 was similar to that for Specimen 1. However, in this case the peak load was 30,000 pounds for the first run, 60,000 pounds for the second run, and 110,000 pounds for the third run. The torque developed in the cable for all runs was identical to that of specimen 1. The cable elongation is shown in Figure D-9. The breaking strength of this specimen was measured at 211,500 pounds, and again, the failure occurred adjacent to the socket.

Cable Specimen 3 was first loaded with a swivel attached at one end. The swivel rotated freely as the load on the cable was increased slowly to 35,000 pounds and then decreased slowly to zero. During this first run the total rotation of the swivel at the peak load was seven revolutions. A permanent set of 0.3 revolution was observed after the load was relaxed.

A second run was made to a peak cable load of 50,000 pounds. This produced 9.7 revolutions of the swivel and an additional permanent set of 0.8 revolution. Finally the swivel was removed, and the specimen was pulled to its breaking point of 212,500 pounds. As with the other specimens, the failure occurred adjacent to the socket.



FIGURE 1. ANCHOR END OF ROPE SPECIMEN IN TENSILE MACHINE

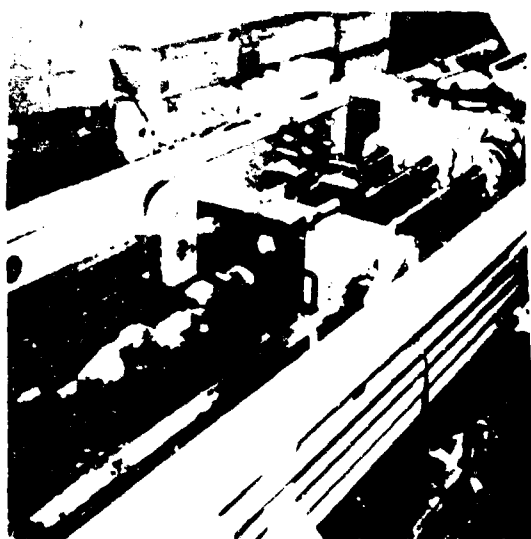


FIGURE 2. LOADING END OF ROPE SPECIMEN IN TENSILE MACHINE

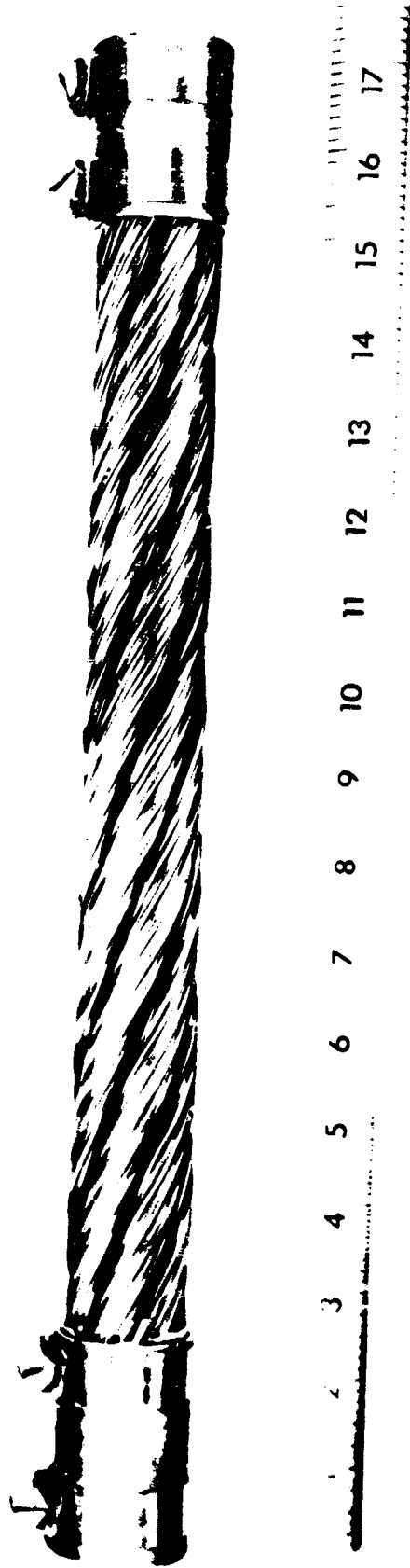
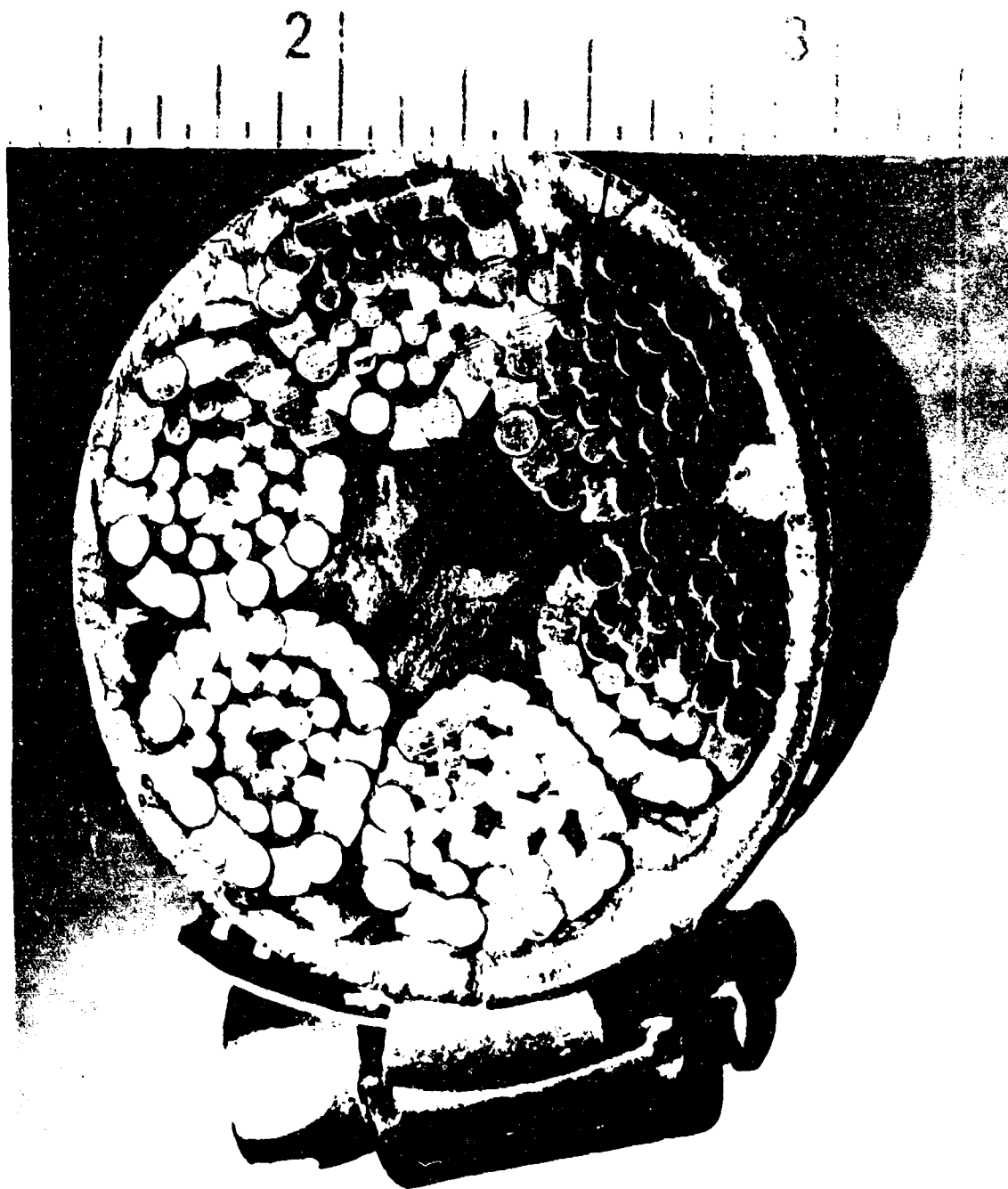


FIGURE 3. EXPERIMENTAL AIRCRAFT-ARRESTING CABLE (CONSTRUCTION E)

37025



37024

FIGURE 4. CROSS SECTION OF CABLE SPECIMEN (CONSTRUCTION E)

During previous tests conducted at the mill, an unsocketed specimen was held in the tensile machine by wedge-type grips and pulled to its breaking point. This specimen failed at the mid-point of its length at a load of 217,500 pounds. As discussed below, this is a more accurate measure of the true breaking strength of this experimental cable.

Examination of each test specimen revealed evidence of corrosion on the wires in the vicinity of the point of failure. It is suspected that this corrosion influenced the failures and produced slightly low values of indicated breaking strength. For this reason the earlier test result of 217,500 pounds breaking strength is a more reliable value.

The corrosion of the rope adjacent to the sockets probably resulted from exposure of the unlubricated wires to moisture during the 3-week period between socketing and testing of the specimens. During the socketing operation, the end of the rope is cleaned of all lubricant and dipped in an acid. This acid is neutralized prior to installation of the socket. Unless care is taken to relubricate the wires following the socketing operation, the wires may corrode rapidly. This corrosion will be accelerated if moisture is present or if some acid residue remains due to improper neutralization.

The curves in Figure D-8 provide a measure of the static elastic modulus of this experimental wire rope. This modulus is calculated using the equation

$$E = \frac{L}{A} \frac{P}{\delta} \quad , \quad (5)$$

where

E = elastic modulus of specimen, psi

A = metallic cross section = 0.966 in.²

L = extensometer gauge length = 100 in.

$\frac{P}{\delta}$ = limiting slope of load-elongation curve, lb/in.

The first load application resulted in an indicated rope modulus of 14.3×10^6 psi. This value increased with progressive runs, and the trend indicates a value of 17.5×10^6 psi for the working modulus of this construction. The increase in elastic modulus with repeated load application is a result of the wires and strands becoming seated in the rope and is common in all cables.

This experimental value of elastic modulus is rather high for a six-strand wire rope. The standard 1-3/8-inch, 6 x 30 Lang-lay, flattened-strand rope presently used for deck pendants has an elastic modulus of about 13×10^6 psi. The high modulus of the experimental rope is due in part to the use of shaped wires which fit together snugly. However, the most influential factor contributing to

the high modulus is the rather long lay length of this particular construction. The lay of this rope may be altered between certain limits to produce the desired characteristics.

The curves shown in Figure D-9 were generated to display the effects of cable load on cable elongation and permanent constructional stretch. As with the curves in Figure D-8, the elastic modulus (slope of curve) for rope Specimen 2 increased with each load application. However, a definite change in the slope of the curve for Run 3 appears at a load equal to the peak load of the previous run. This suggests that constructional stretch of the specimen progresses markedly with increasing load level. This permanent elongation of the rope results from seating of the wires and strands and equalization of the loads and stresses in the construction.

The rotation tests conducted on Specimen 3 displayed several characteristics of this experimental rope. First, the rope unlays quite readily when loaded with no rotational restraint. (This is true for all Lang-lay ropes.) At a 50,000-pound load, the rope unlaid approximately 10 of the 15 lays initially present. Furthermore, when the load was released, the rope immediately regained nine of these turns. This indicates that very little permanent deformation resulted from this severe unwrapping that increased the lay length from about 11 to nearly 34 inches. Subsequent testing to failure indicated further that the breaking strength of this specimen was not affected by the rotation test.

Testing Constructions B, C, D, and F

The test procedures were modified slightly for Constructions B, C, D, and F. For these ropes, two specimens of each construction were tested for torsion, elastic modulus, and ultimate strength, but the rotation tests using the swivel were eliminated. It became apparent that the rotation test had little practical value for the arresting-cable application.

The first specimen of each construction was loaded and then unloaded slowly ten times to a peak tension of 100,000 pounds. The torque developed by each specimen did not change from the first to the last run. However, as for Construction E, the elongation and, therefore, the elastic modulus did not remain constant. The modulus changed measurably during the first three runs and then changed very little during the remaining loading cycles.

The second specimen of each construction was given the same number of loading cycles, but to a maximum load of 150,000 pounds. Again, rope elongation was recorded.

Each specimen, following its tests for torsion and elongation, was loaded to failure. As in the tests of Construction E, several of the ropes failed at a socket. Inspection of these failures revealed evidence of corrosion. It is likely that every specimen would have easily exceeded the requested 188,000-pound minimum breaking strength if it had not been for premature failure at a socket.

The results of all torsion and elongation tests are presented in Appendixes C and D. All measured wire-rope characteristics including the ultimate strength are tabulated in Appendix E. The values for elastic modulus presented in Appendix E were calculated using Equation (5) and the appropriate values of extensometer gage length, wire-rope metallic area (see Appendix B), and limiting slope of the load-elongation curve.

The test data reveal that wire-rope construction A, the standard deck pendant, has both a lower elastic modulus and a higher developed torque than do the other constructions. This is attributable, for the most part, to the shorter lay length of this rope (see Appendix B). It should be noted that the rope lay of each of these constructions can be shortened or lengthened within limits to produce the desired characteristics. For the arresting-cable application, a lower elastic modulus is desirable.

Tests of Wire-Rope Flexibility

The flexibility of a wire rope is an indicator of the internal stresses in the construction which result from bending. While there is no established method of measuring wire-rope flexibility or identifying this parameter quantitatively, a simple test may be used to obtain a comparison of the relative flexibility of two or more ropes.

Each of the six arresting-cable constructions was evaluated for flexibility by wrapping a length of the rope around a sheave as shown in Figure 5. The free end of the specimen was pulled down with a spring scale to a predetermined level. The force required to achieve this bend was recorded, and this provided a measure of the flexibility of the construction.

Each of the rope specimens had a slight permanent curvature resulting from storage on a reel. Therefore, two tests were performed on each rope: for one test, the rope was bent in the same plane and direction as the initial curvature, and for the second test, the rope was bent in the same plane but opposite direction of the initial curvature. The results of these two tests were then averaged to provide the measure of flexibility.

The results of this investigation are presented in Appendix E. For purposes of comparison, the standard deck-pendant rope, Construction A, is assigned a value for flexibility of one. The values given in Table E-1 were calculated as follows:

$$\text{Relative Flexibility} = \frac{F_A}{F_1}$$

where

F_A = force required to bend wire-rope Construction A, lb

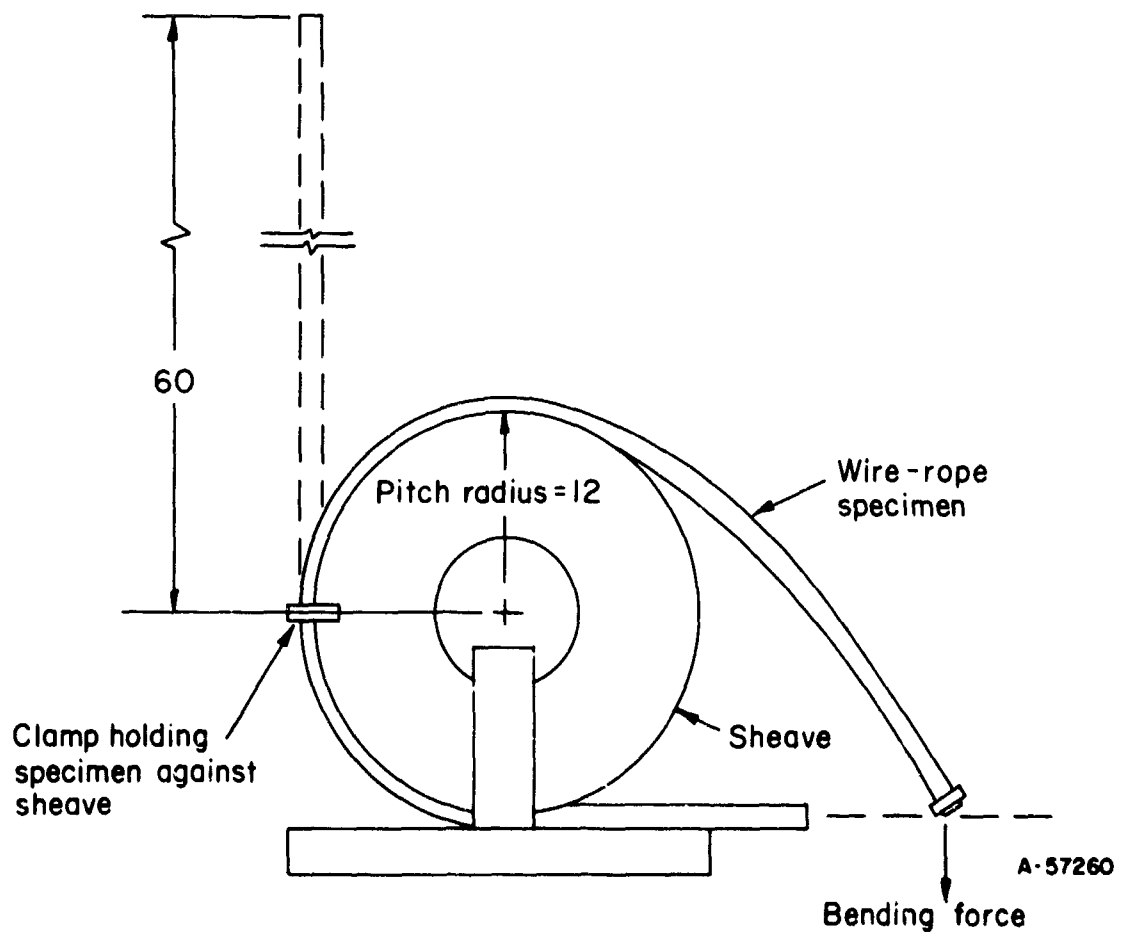


FIGURE 5. APPARATUS USED TO MEASURE WIRE-ROPE FLEXIBILITY

F_i = force required to bend the wire-rope construction
in question, lb (i = B, C, D, E, or F)

The higher the numerical value of relative flexibility, the smaller was the force required to produce the bend. It is noteworthy that the experimental arresting cable, Construction E, which has the greatest metallic area and ultimate strength, is also the most flexible.

Transverse-Impact Tests

Any wire rope that is used for the deck pendant must resist damage due to external abrasion and arresting-hook impact. It has been found through deck-pendant failure analyses that the hook impact produces the following types of rope deterioration:

- (1) Failure of outer wires at points of interstrand, crossed-wire notching
- (2) Failure of outer wires at points of contact with the arresting hook
- (3) Failure of internal wires due to wire notching
- (4) Crushing, shreading, and parting of the fiber core.

A transverse-impact test has been devised to simulate actual aircraft engagement with the deck pendant. For this test, an arresting hook mounted on a small carriage and guided by a steel track is propelled by a cannon charged with smokeless powder. This apparatus is shown in Figure 6. Figure 7 shows the cannon and hook point ready for firing.

For each test a 30-foot length of the wire rope is placed perpendicular to the track so as to be impacted at its midpoint. The positions of the rope and the hook at the instant of impact are shown in Figure 8. The ends of the specimen are not anchored or restrained in any way.

The impact of the hook produces tensile waves in the rope which propagate to the ends of the specimen and are reflected. The reflected waves return the rope stress to zero as they propagate back to the impact point. Since the propagation velocity of these waves is approximately 10,000 feet/second, the section of the rope at the point of impact is in tension for about 0.003 second. During this time, the carriage moves about six inches, causing the rope to wrap onto the hook and form a kink wave on either side of the hook. Although this time interval is quite short, the impact loads generated between the rope and the hook closely simulate an actual aircraft engagement. It is during this initial impact that the rope receives severe damage.

Following impact with the specimen, the carriage is slowed to a stop by three lead weights placed on the track. Blocks of wood cushion the impact of the carriage with the weights. This is shown in Figure 9.



FIGURE 6. APPARATUS USED FOR TRANSVERSE-IMPACT TESTS



FIGURE 7. CANNON WITH HOOK POINT READY FOR FIRING

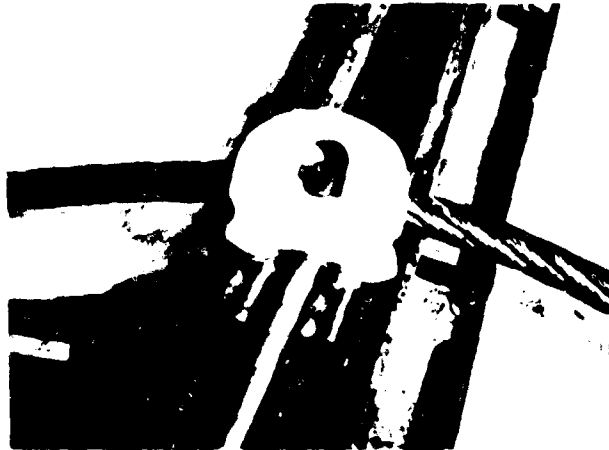


FIGURE 8. POSITIONS OF HOOK POINT AND WIRE-ROPE SPECIMEN AT INSTANT OF IMPACT



FIGURE 9. WEIGHTS USED TO DECELERATE HOOK



FIGURE 10. ROPE MOTION FOLLOWING IMPACT

The rope specimen maintains contact with the hook only during the 0.003-second time period mentioned above. At the end of this time, the entire length of rope is in motion and its inertia carries it into the air and off the end of the track. Figure 10 shows the cable motion during a typical impact test. The specimen shown in this figure had experienced a number of hits. The brooming of the cable ends results from the reflection of the tensile waves produced by impact.

One specimen each of the six rope constructions under test was marked at its midpoint and subjected to four hook impacts at this point. An impact velocity of 200 feet/second (118 knots) was the test goal as this is a common engaging velocity experienced in actual service. This goal was met within ± 4 percent for all tests; the actual impact velocities are tabulated in Appendix F. The velocity of the hook was measured by allowing the carriage to break two fine copper wires spanning the track just prior to impact with the rope specimen. Parting of the first wire turned on a high-speed counter and parting of the second wire turned off the counter. The time interval and the distance between the velocity wires (2 feet) were then used to calculate the hook velocity.

Photographs showing rope damage resulting from the impact tests are included in Appendix G. Figures G-1 through G-4 are views of the rope displaying the contact area with the hook and the permanent kink at the impact point. The flattening of the rope in the impact area is also obvious in these figures. Measurements of the permanent kink angle and the flattening of the rope are tabulated in Appendix H.

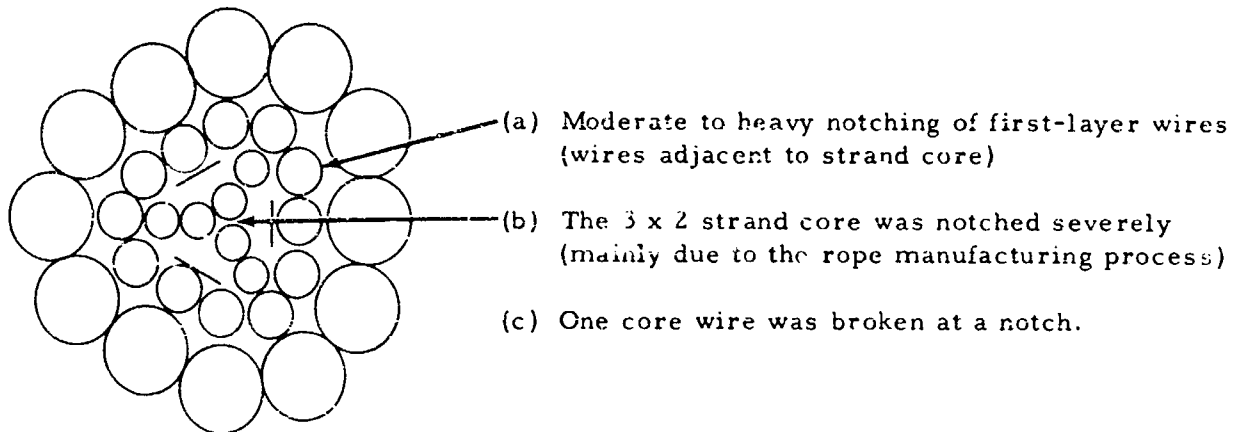
Figure G-5 shows the fiber cores that were removed from the specimens. The sisal-fiber core from Construction A is quite ragged and completely severed at the impact point. The polypropylene fiber core from Construction E is also heavily damaged in the impact area. However, the nylon-fiber cores from the other specimens display no detectable deterioration. This exemplifies the superior qualities of nylon in resisting impact damage. This elasticity of this material allows the core fibers to elongate without breaking and to return to their initial condition.

The two most heavily damaged strands from each specimen are shown in detail in Figures G-6 through G-17. Views of both the impact side and the reverse side of the strands are included. In every case, the damage due to contact with the hook appears as a general denting and roughening of the wires. No truly severe surface damage was produced by the limited number of impacts.

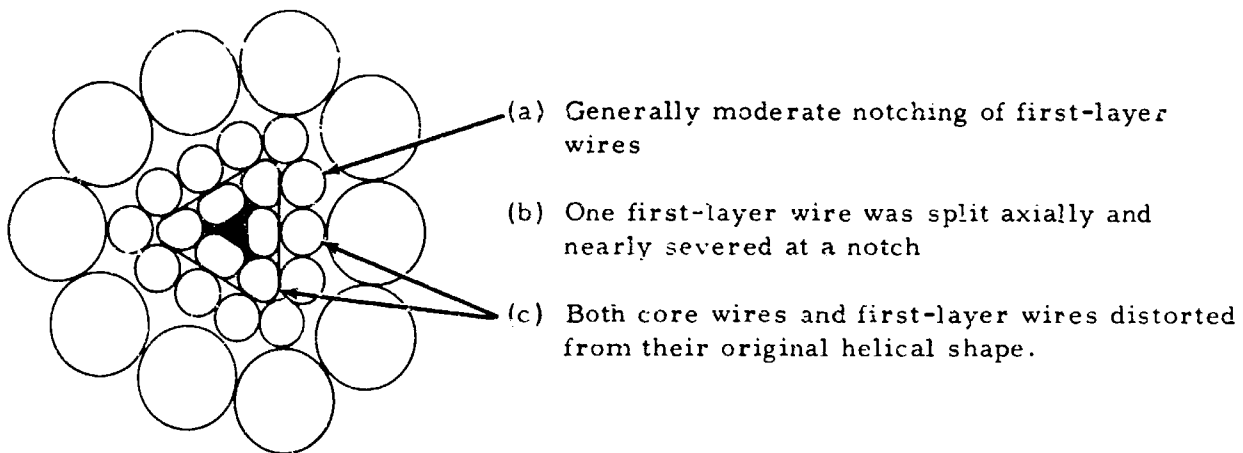
Similarly, the reverse sides of the strands show no severe wire notching due to interstrand contact. More obvious is a lateral displacement of several wires in all specimens except Construction A. Figure G-7 shows how some of the sisal fibers of the rope core in Construction A became pinched between the wires. This also happened, but to a lesser degree, with the polypropylene core in Construction E (Figure G-15).

Disassembly of the strands revealed some inner-wire notching in all specimens. This notching was more severe in some constructions than in others. The condition of the interior of the strands may be summarized as follows:

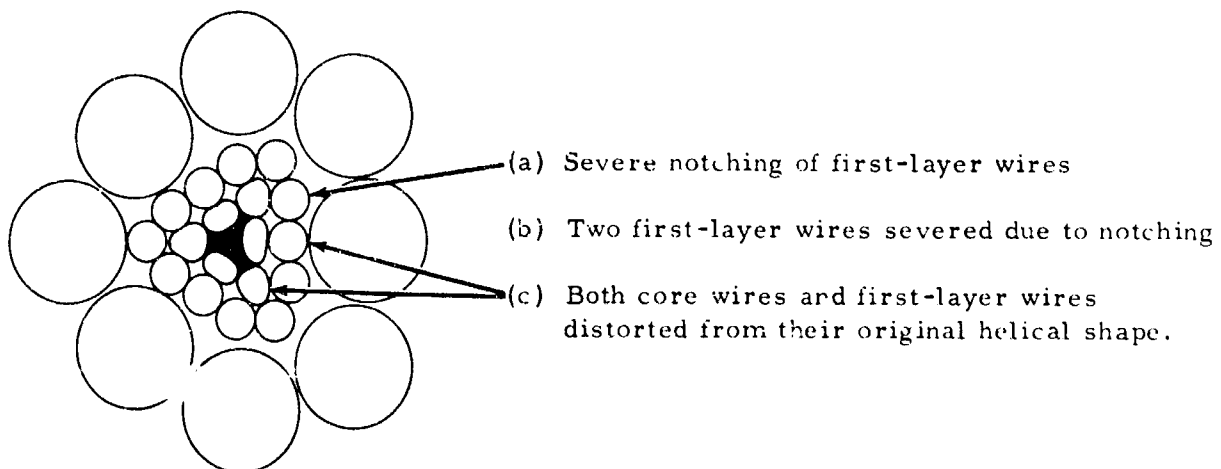
(1) Construction A



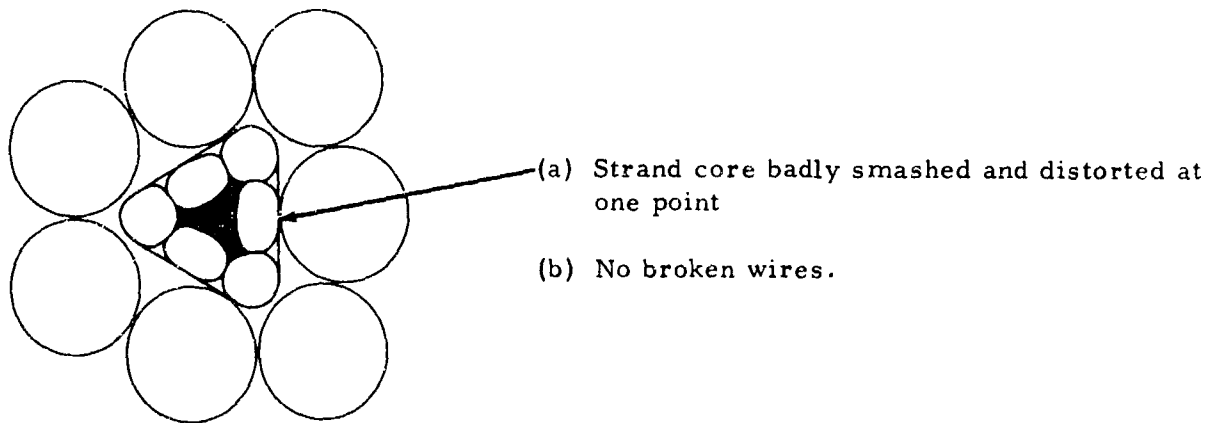
(2) Construction B



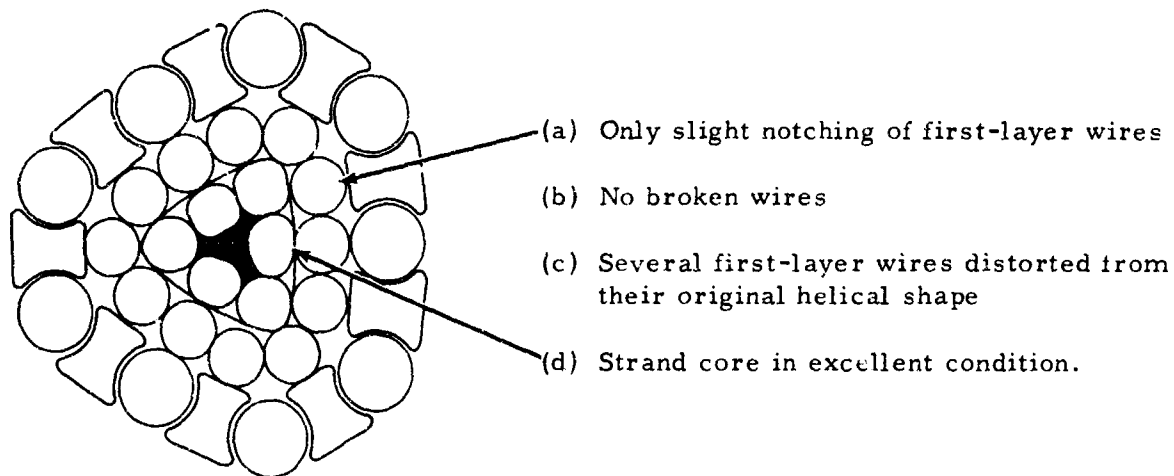
(3) Construction C



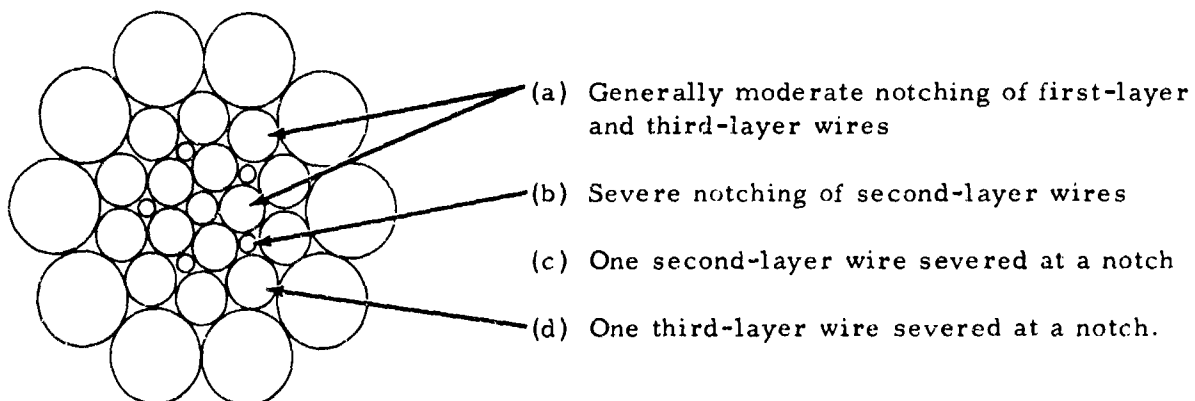
(4) Construction D



(5) Construction E



(6) Construction F



APPENDIX A

WIRE-ROPE CONSTRUCTIONS SELECTED FOR
EXPERIMENTAL EVALUATION



FIGURE A-1. CONSTRUCTION A, 1-3/8-INCH, 6 X 30, LANG-LAY, FLATTENED-STRAND ROPE

The Standard Construction Presently Used for Deck Pendants

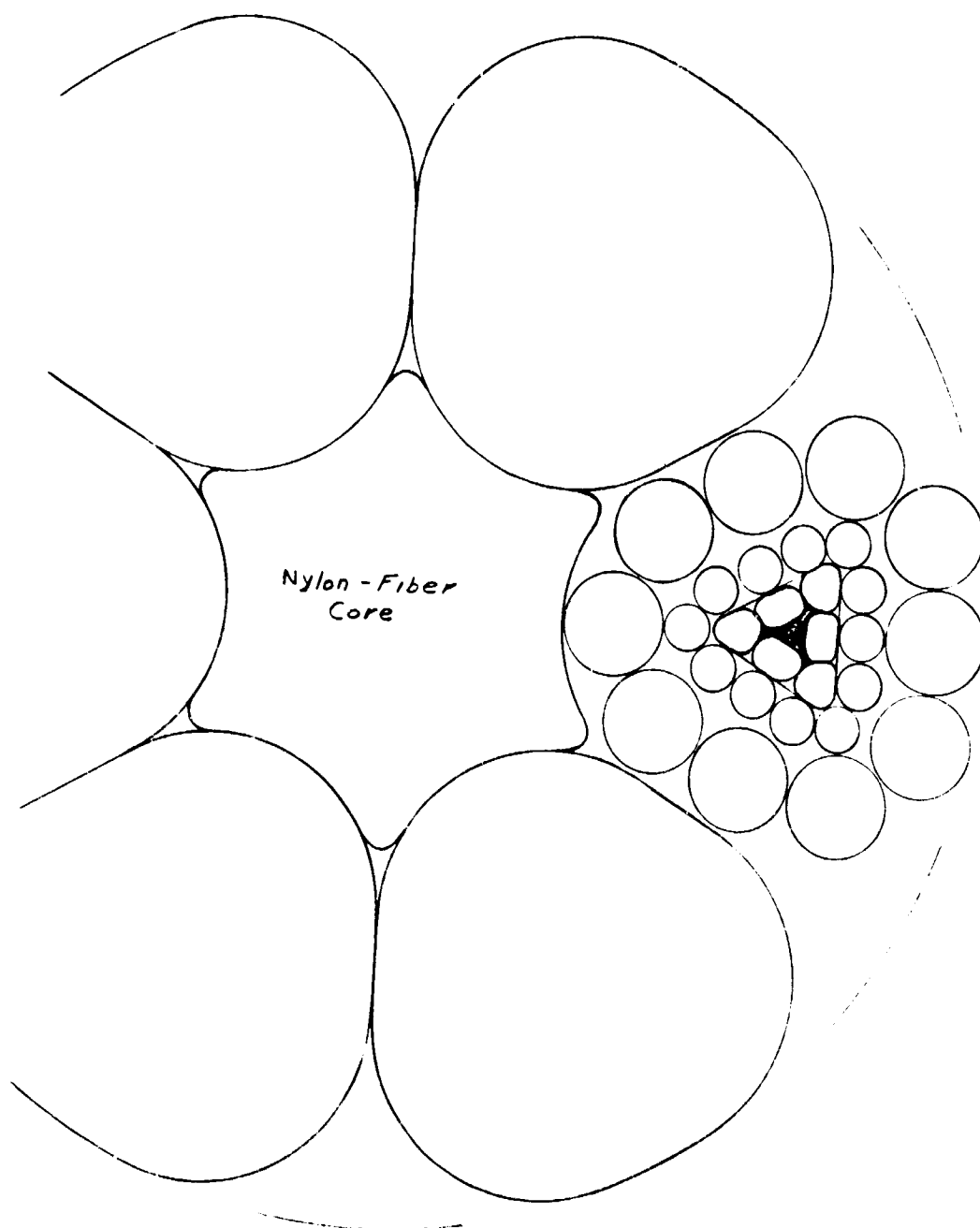


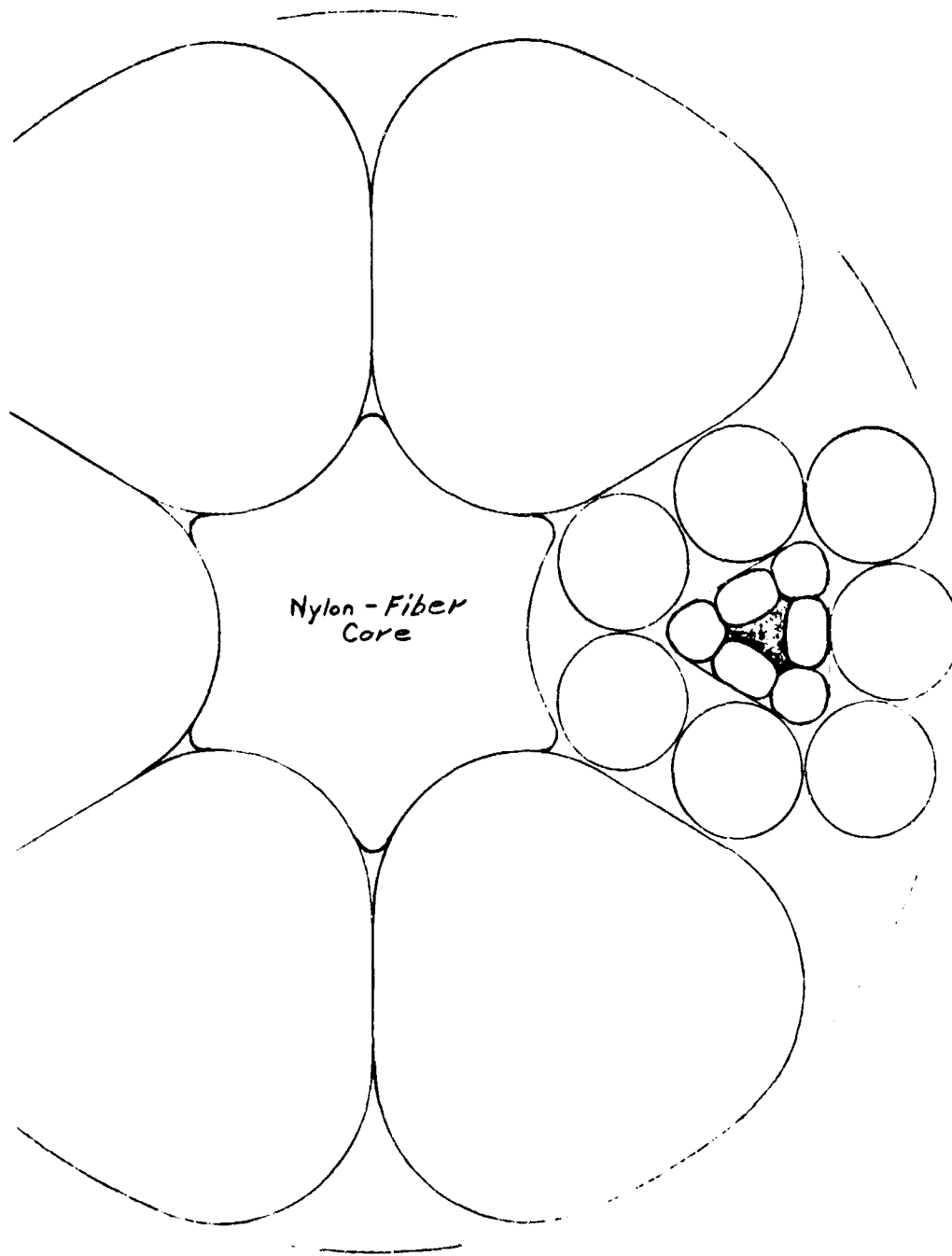
FIGURE A-2. CONSTRUCTION B, 1-3/8-INCH, 6 X 10/12/BRANGLE,
LANG-LAY, FLATTENED-STRAND ROPE

Nylon-rope core, seven-wire drawn strand for strand
core.



FIGURE A-3. CONSTRUCTION C, 1-3/8-INCH, 6 X 8/12/BRANGLE, LANG-LAY, FLATTENED-STRAND ROPE

Nylon-rope core. seven-wire drawn strand for strand core.



**FIGURE A-4. CONSTRUCTION D, 1-3/8-INCH, 6 X 7/BRANGLE,
LANG-LAY, FLATTENED-STRAND ROPE**

Nylon-rope core, seven-wire drawn strand for
strand core.

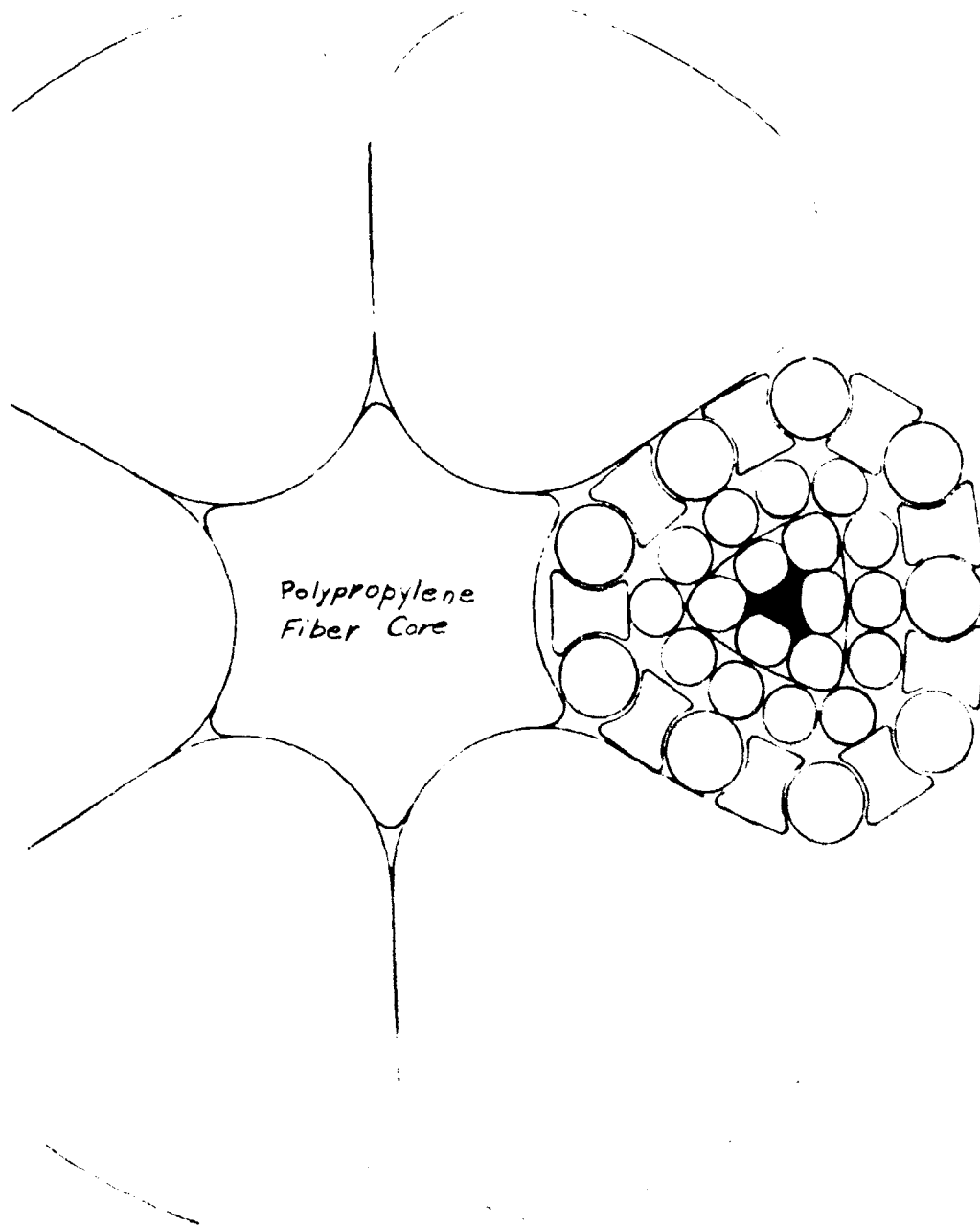


FIGURE A-5. CONSTRUCTION E, 1-3/8-INCH, 6 X 36 HALF-LOCK, LANG-LAY, FLATTENED-STRAND ROPE

Polypropylene-rope core, six-wire drawn strand for strand core.

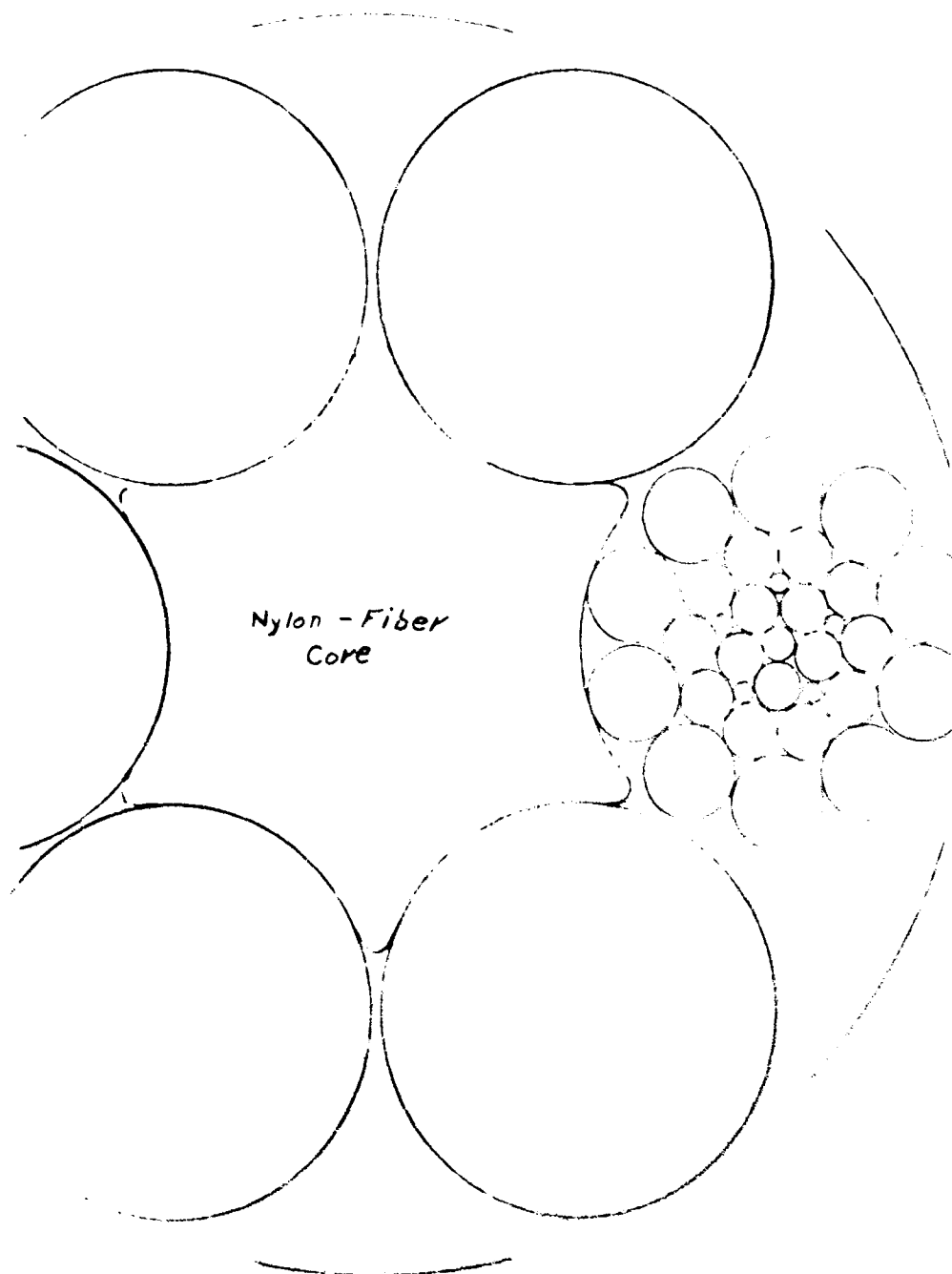


FIGURE A-6. CONSTRUCTION F, 1-3/8-INCH, 6 x 31,
LANG-LAY, ROUND-STRAND ROPE

Nylon-rope core.

APPENDIX B

WIRE-ROPE PHYSICAL PROPERTIES

TABLE P-1. WIRE-ROPE PHYSICAL PROPERTIES

Construction A: 1-3/8-inch, 6 x 30, Lang-lay,
 flattened-strand wire rope;
 rope core: sisal fiber
 actual rope diameter: 1.420 inches
 rope lay: 9.50 inches

Wire Location	Total Number	Wire Diameter, inch	Approximate Wire Strength ^(a) , psi	Total Area, inch ²
Strand core	36	0.057	230,000	0.0919
First layer	72	0.062	280,000	0.2174
Second layer	72	0.102	260,000	0.5882
				0.8975

(a) Approximate per standard practice.

Construction B: 1-3/8-inch, 6 x 10/12/Brangle,
 Lang-lay, flattened-strand wire rope;
 rope core: nylon fiber
 actual rope diameter: 1.410 inches
 rope lay: 10.50 inches

Wire Location	Total Number	Wire Diameter, inch	Average Wire Strength, psi	Total Area, inch ²
Brangle core	6	0.061	134,500	0.0175
Brangle core	36	0.058	262,000	0.0950
First layer	72	0.054	272,000	0.1649
Second layer	60	0.112	268,000	0.5910
				0.8684

Construction C: 1-3/8-inch, 6 x 8/12/Brangle,
 Lang-lay, flattened-strand wire rope;
 rope core: nylon fiber
 actual rope diameter: 1.388 inches
 rope lay: 10.50 inches

Wire Location	Total Number	Wire Diameter, inch	Average Wire Strength, psi	Total Area, inch ²
Brangle core	6	0.051	132,800	0.0122
Brangle core	36	0.049	265,000	0.0680
First layer	72	0.046	268,000	0.1195
Second layer	48	0.130	267,500	0.6370
				0.8367

TABLE B-2. (Continued)

Construction D: 1-3/8-inch, 6 x 7/Brangle, Lang-lay,
 flattened-strand wire rope;
 rope core: nylon fiber
 actual rope diameter: 1.423 inches
 rope lay: 10.45 inches

Wire Location	Total Number	Wire Diameter, inch	Average Wire Strength, psi	Total Area, inch ²
Brangle core	6	0.072	105,000	0.0244
Brangle core	36	0.072	279,000	0.1465
Outer layer	42	0.148	264,500	0.7224
				0.8933

Construction E: 1-3/8-inch, 6 x 36, half-lock, Lang-lay, flattened-strand wire rope;
 rope core: polypropylene fiber
 actual rope diameter: 1.453 inches
 rope lay: 10.50 inches

Wire Location	Total Number	Wire Diameter, inch	Average Wire Strength, psi	Total Area, inch ²
Strand core	36	0.065	237,000	0.1195
First layer	72	0.061	274,000	0.2104
Outer (round)	54	0.090	294,000	0.3434
Outer (half-lock)	54	0.090 x 0.052	221,000	0.2862
				0.9595

Construction F: 1-3/8-inch, 6 x 31, Lang-lay, round-strand wire rope;
 rope core: nylon fiber
 actual rope diameter: 1.410 inches
 rope lay: 8.80 inches

Wire Location	Total Number	Wire Diameter, inch	Average Wire Strength, psi	Total Area, inch ²
Strand core	6	0.043	237,000	0.0087
First layer	30	0.056	230,000	0.0738
Second layer	30	0.025	292,000	0.0147
Third layer	60	0.061	324,000	0.1752
Fourth layer	60	0.102	308,000	0.4902
				0.7626

APPENDIX C

WIRE-ROPE TORQUE CHARACTERISTICS

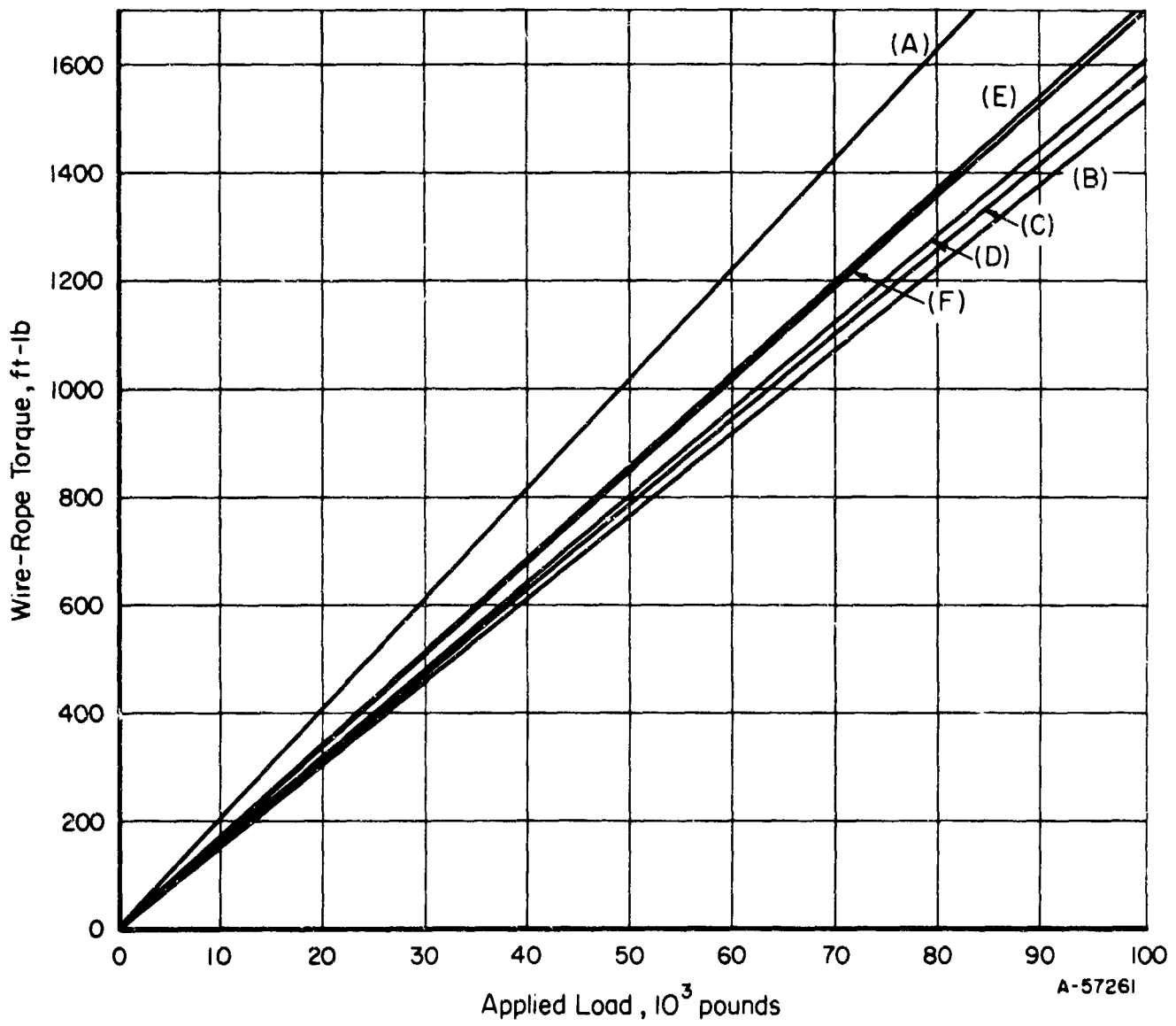


FIGURE C-1. WIRE-ROPE TORQUE CHARACTERISTICS

APPENDIX D

WIRE-ROPE LOAD-ELONGATION CURVES

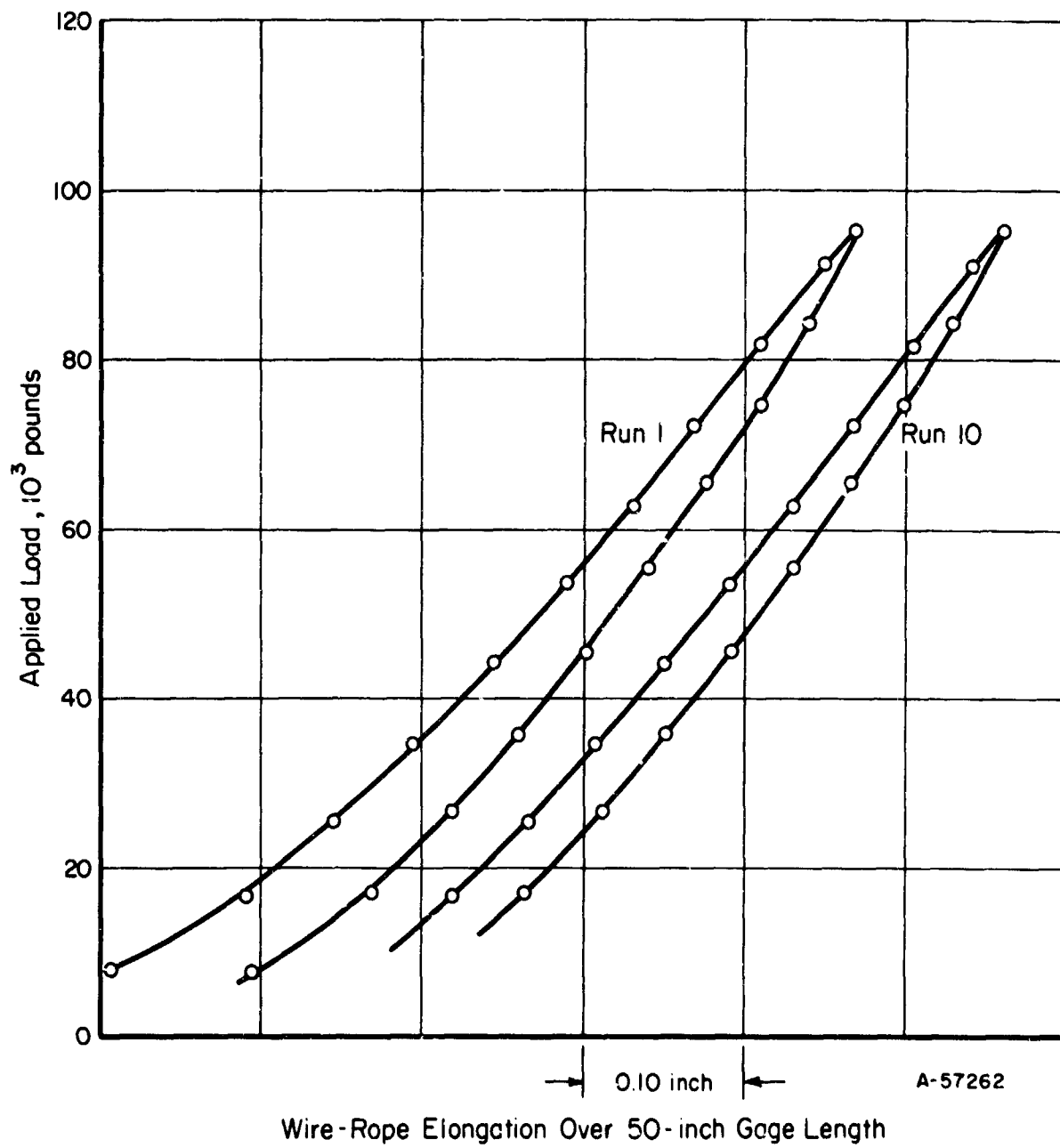


FIGURE D-1. LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION A

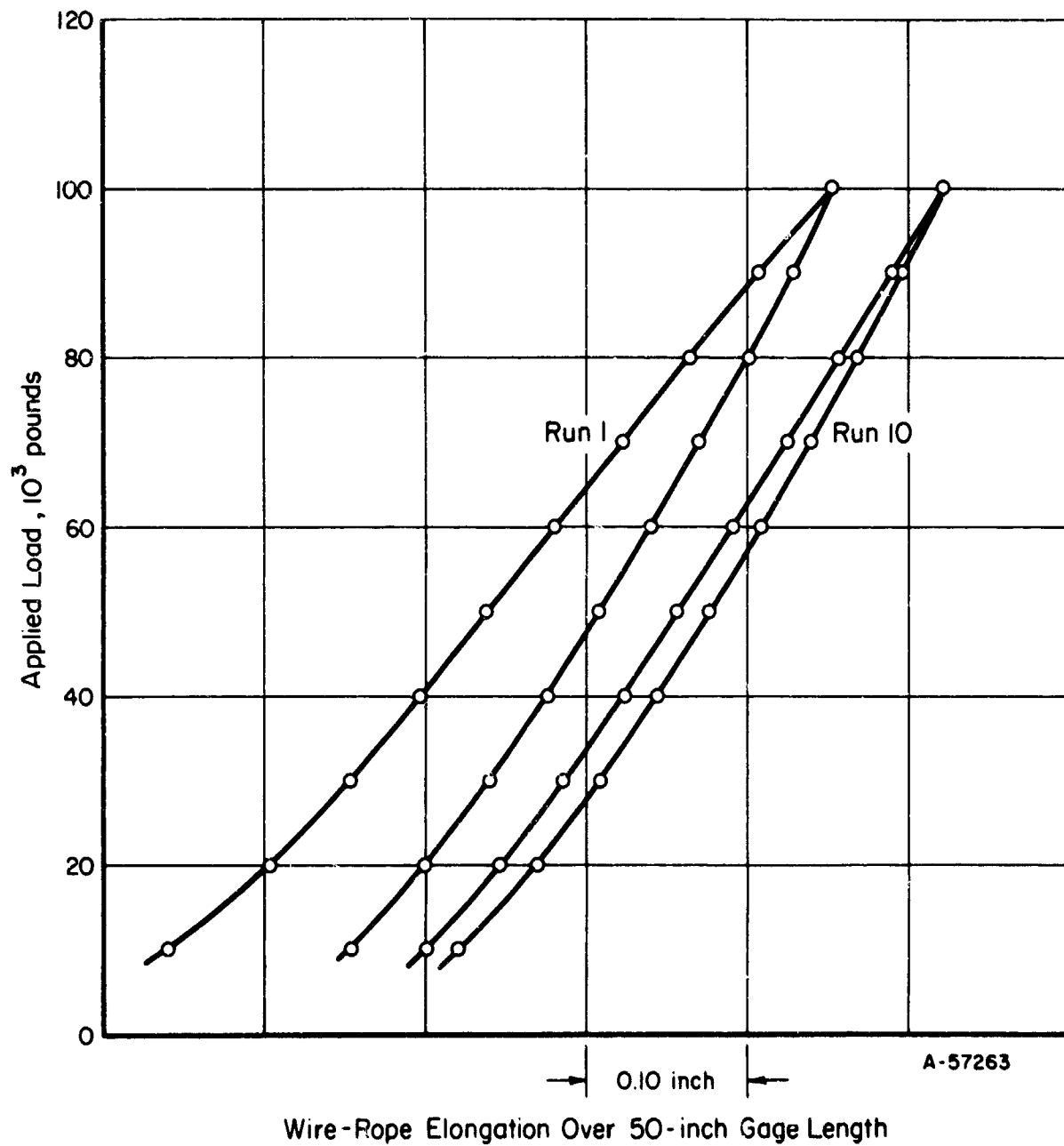


FIGURE D-2. LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION B, SPECIMEN 1

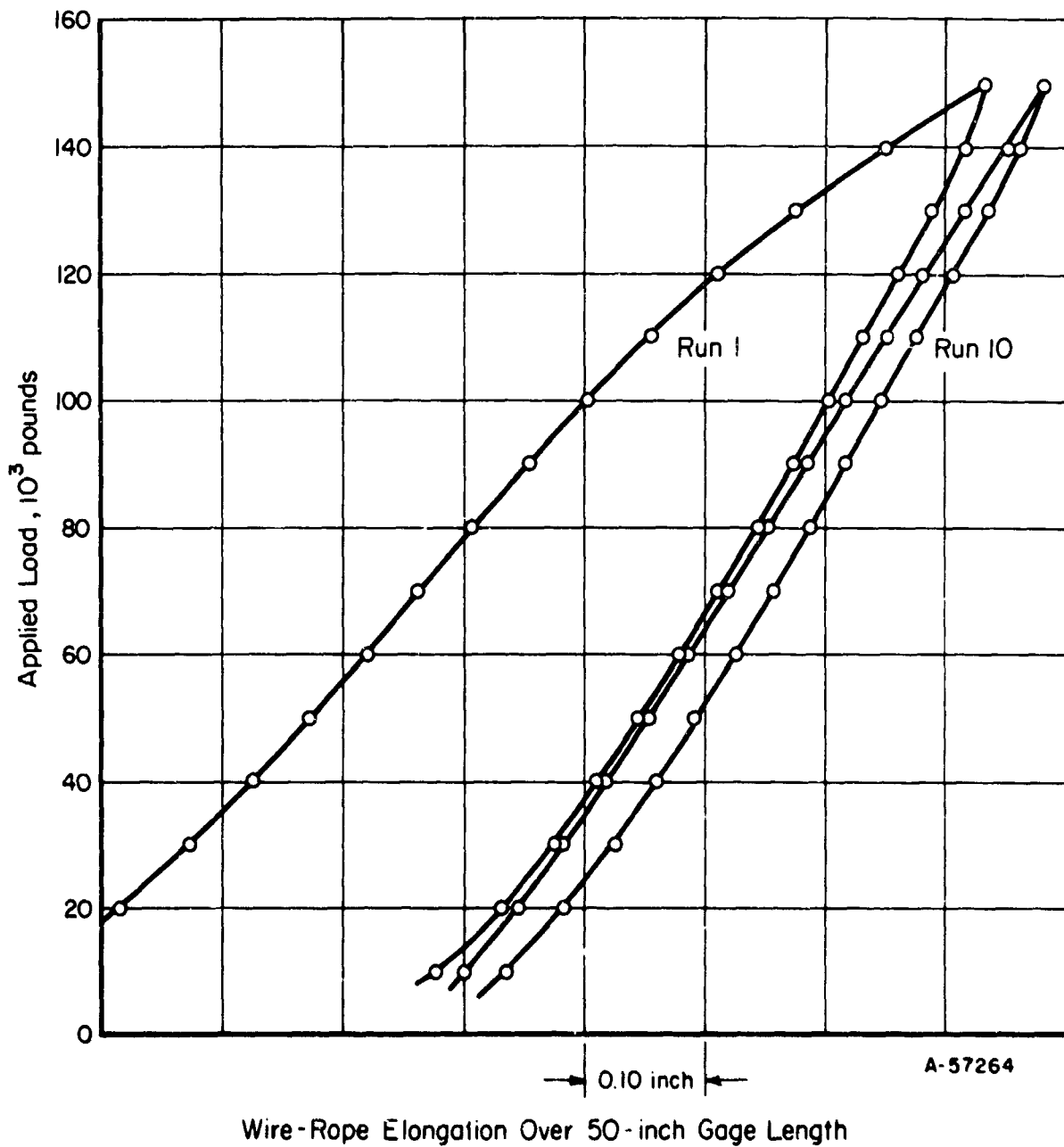


FIGURE D-3. LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION B, SPECIMEN 2

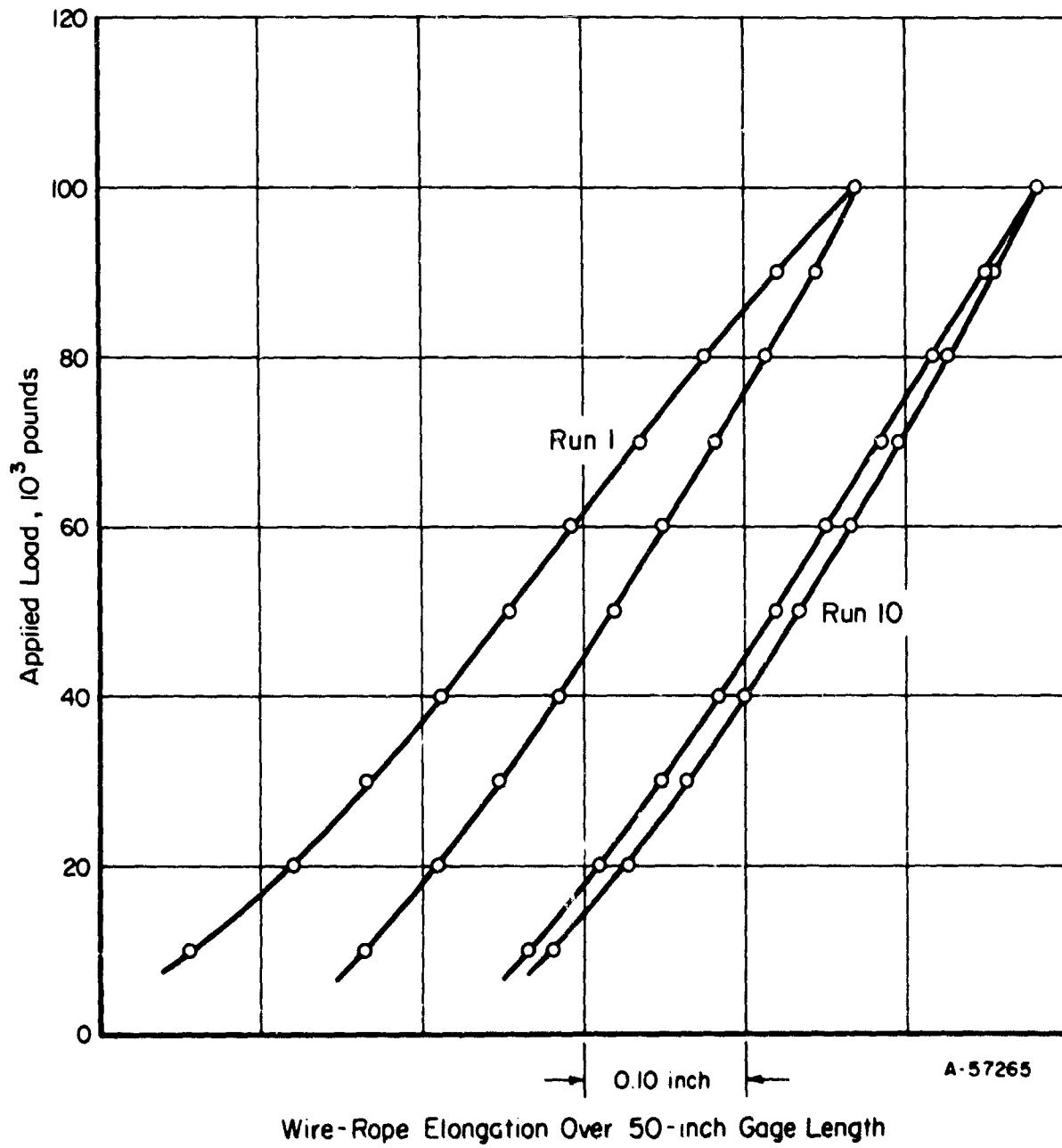


FIGURE D-4. LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION C, SPECIMEN 1

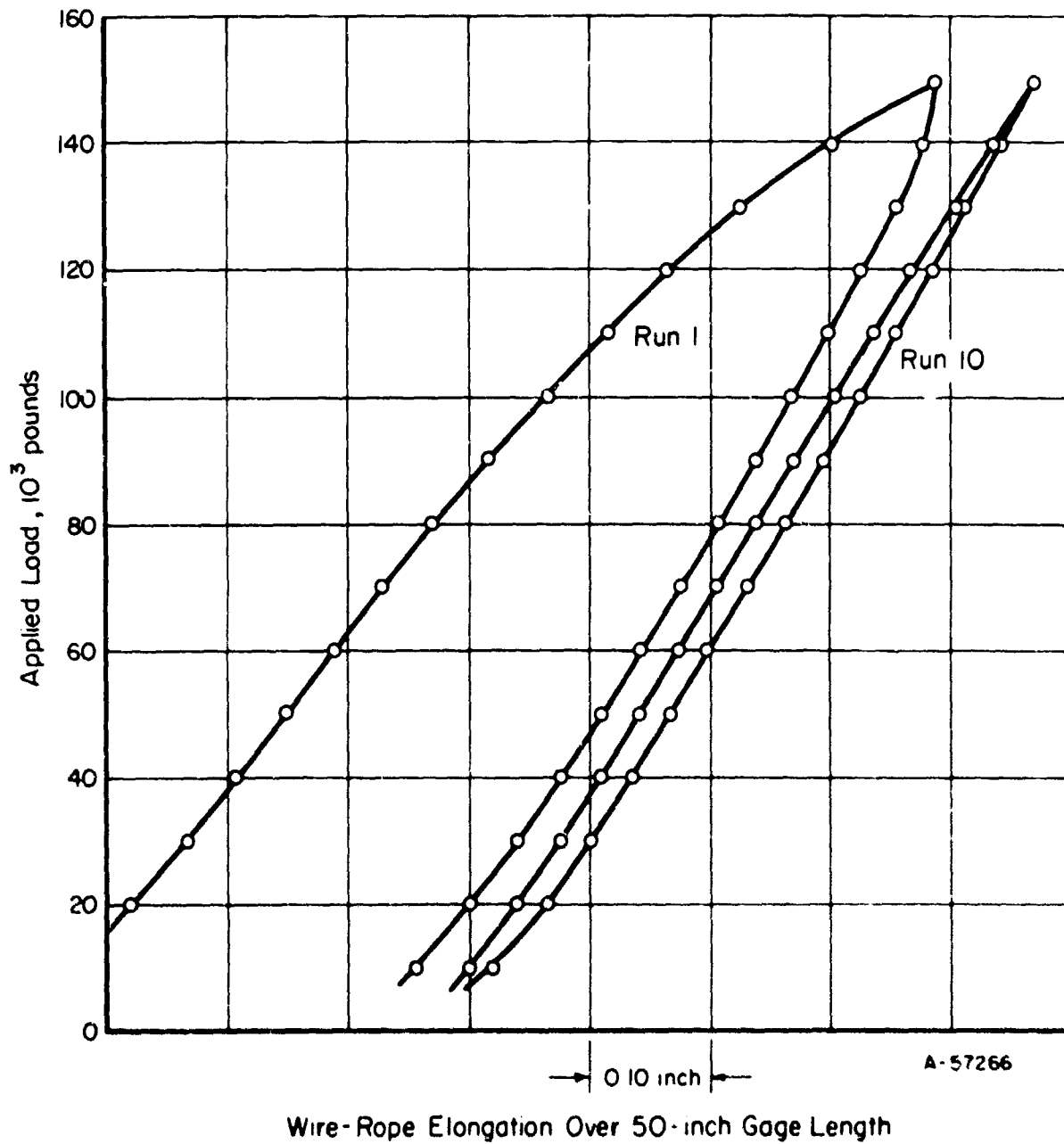


FIGURE D-5. LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION C, SPECIMEN 2

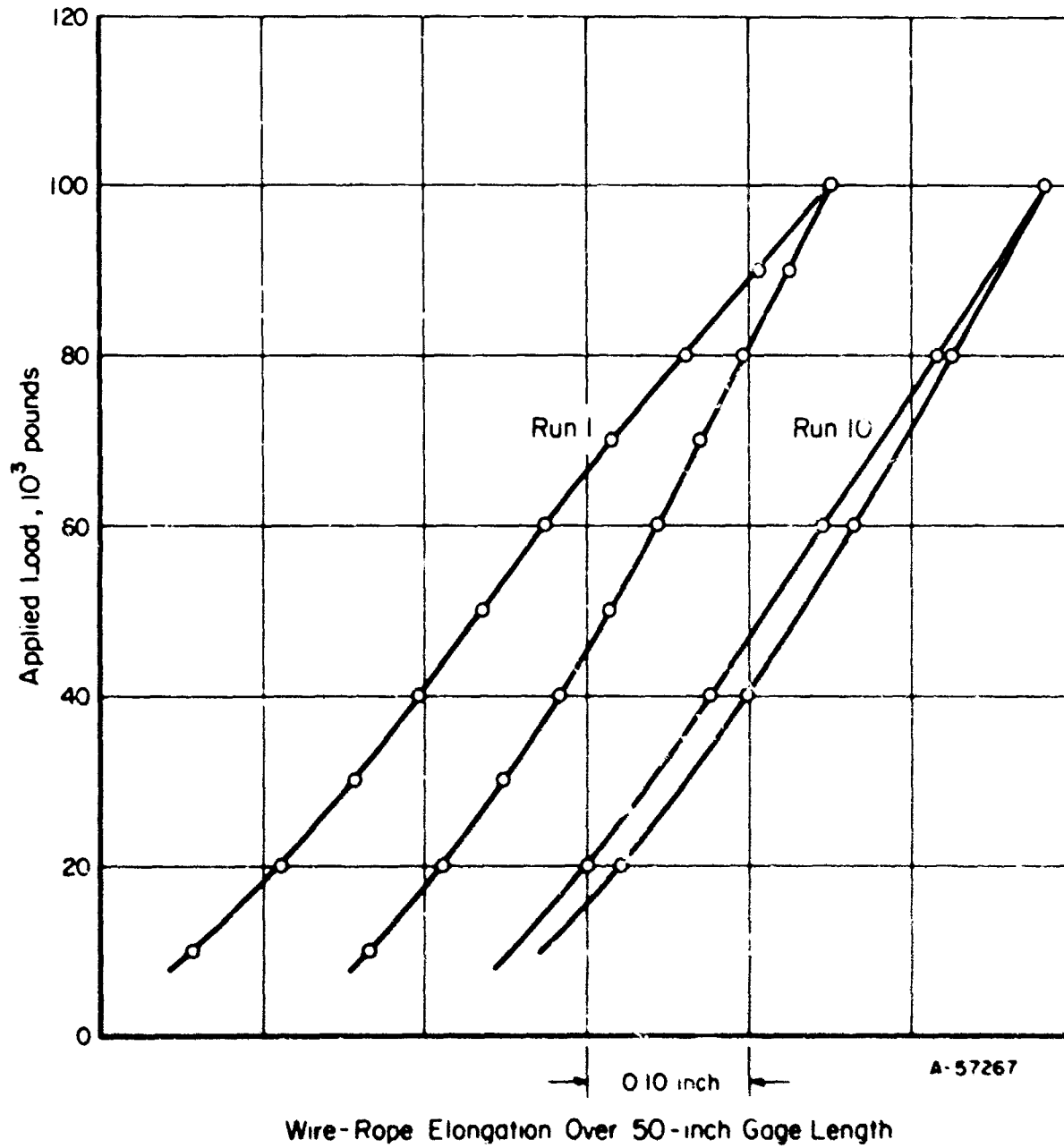


FIGURE D-6 LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION D, SPECIMEN 1

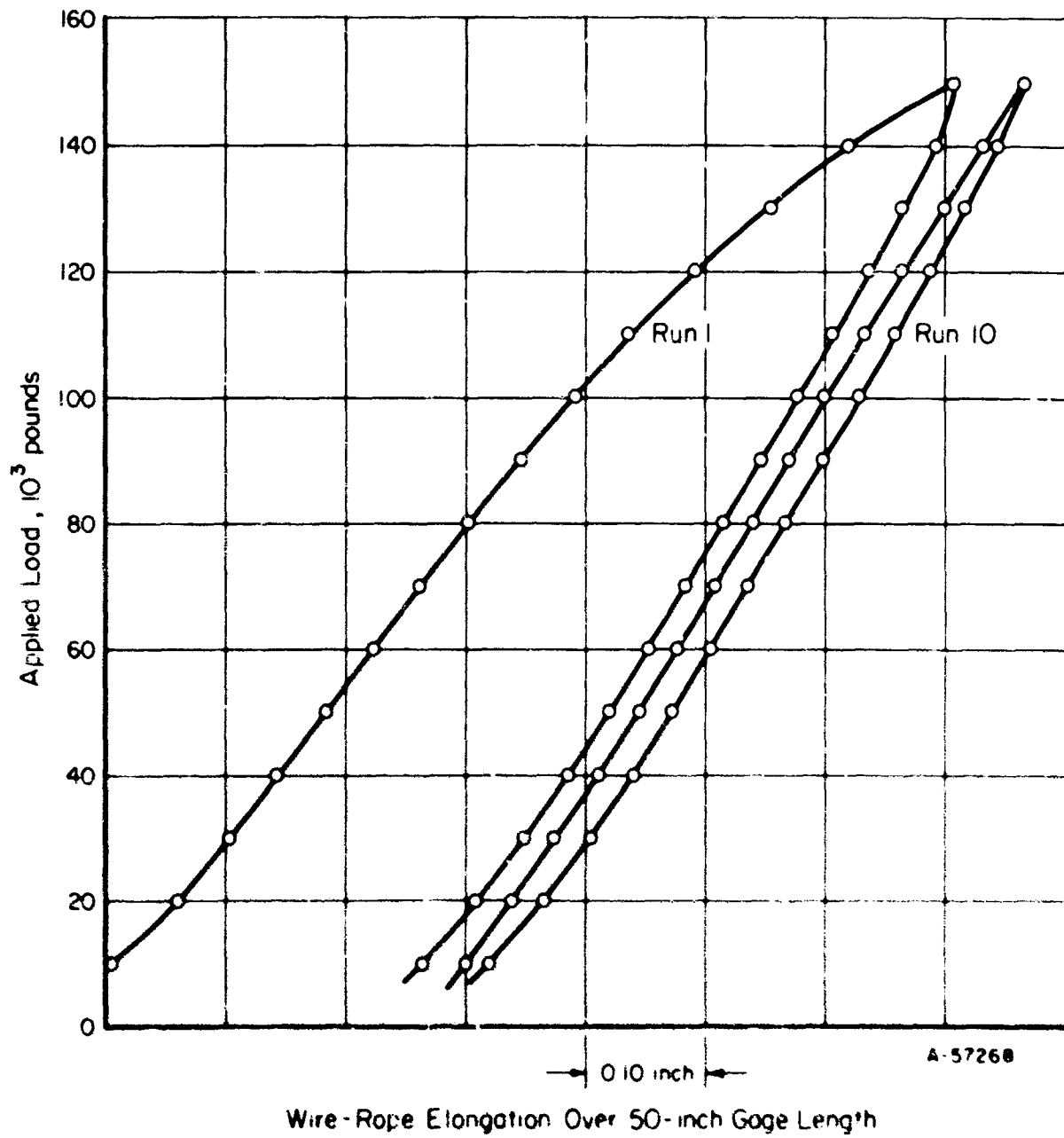


FIGURE D-7. LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION D, SPECIMEN 2

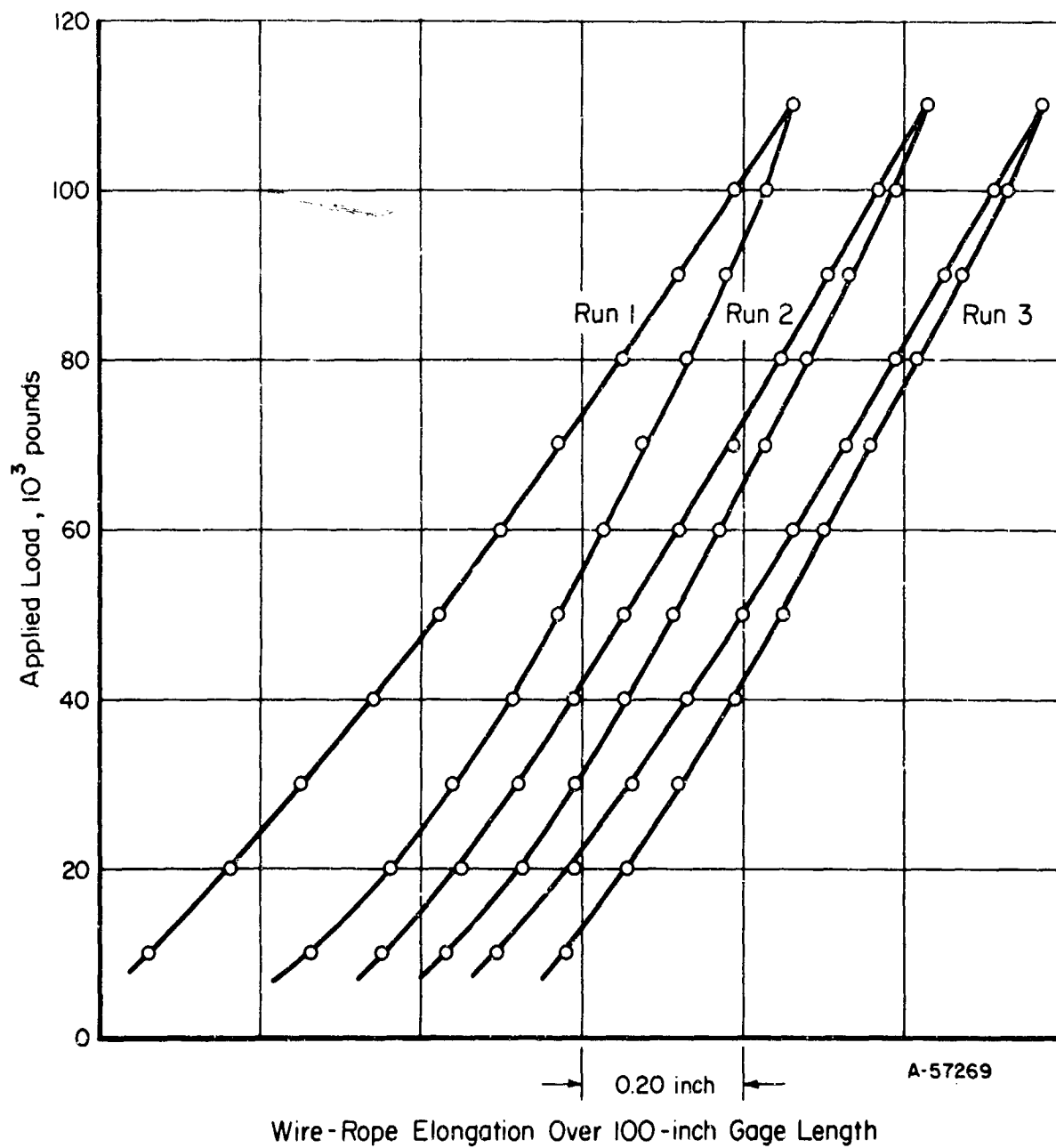


FIGURE D-8. LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION E, SPECIMEN 1

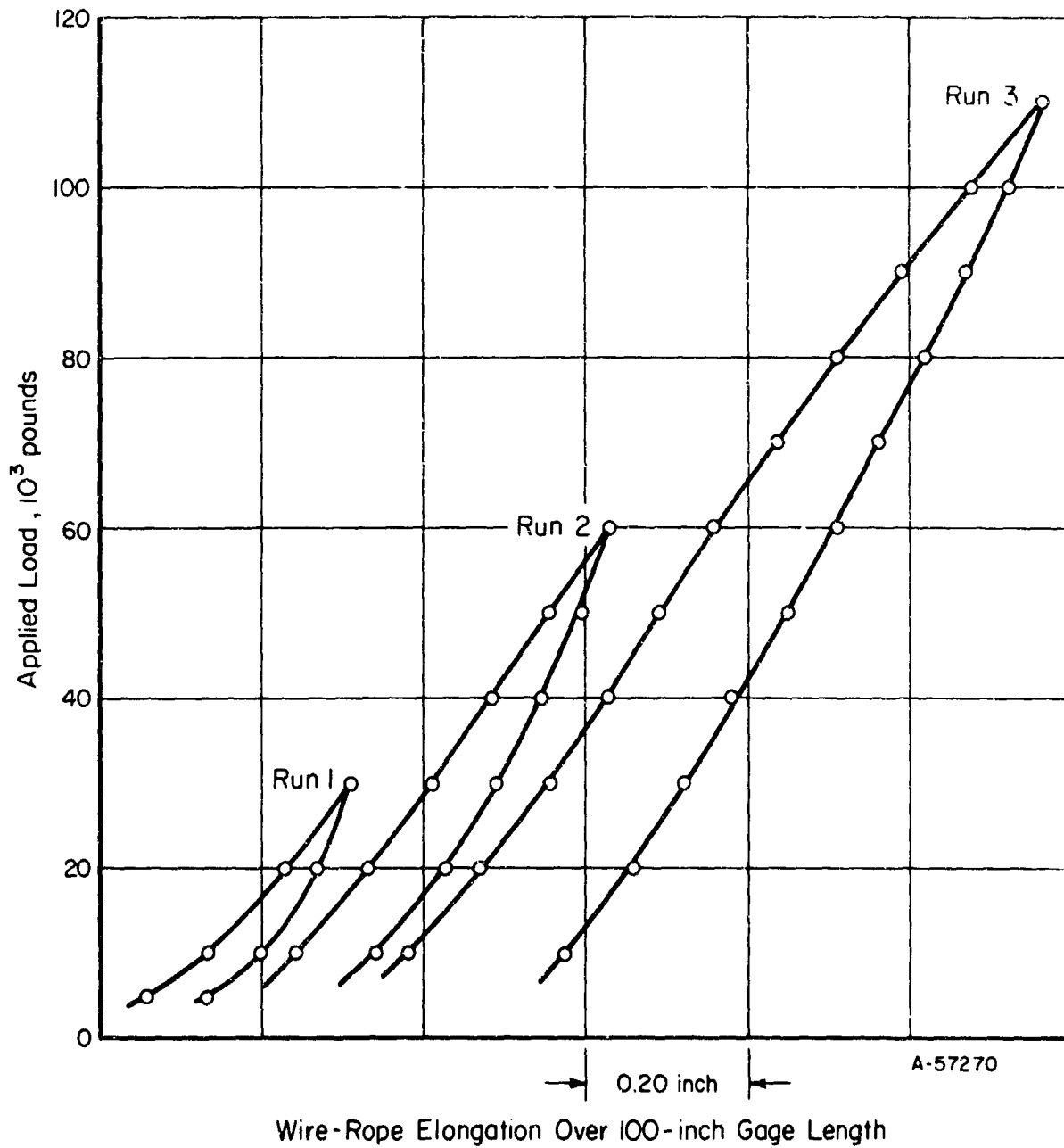


FIGURE D-9. LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION E, SPECIMEN 2

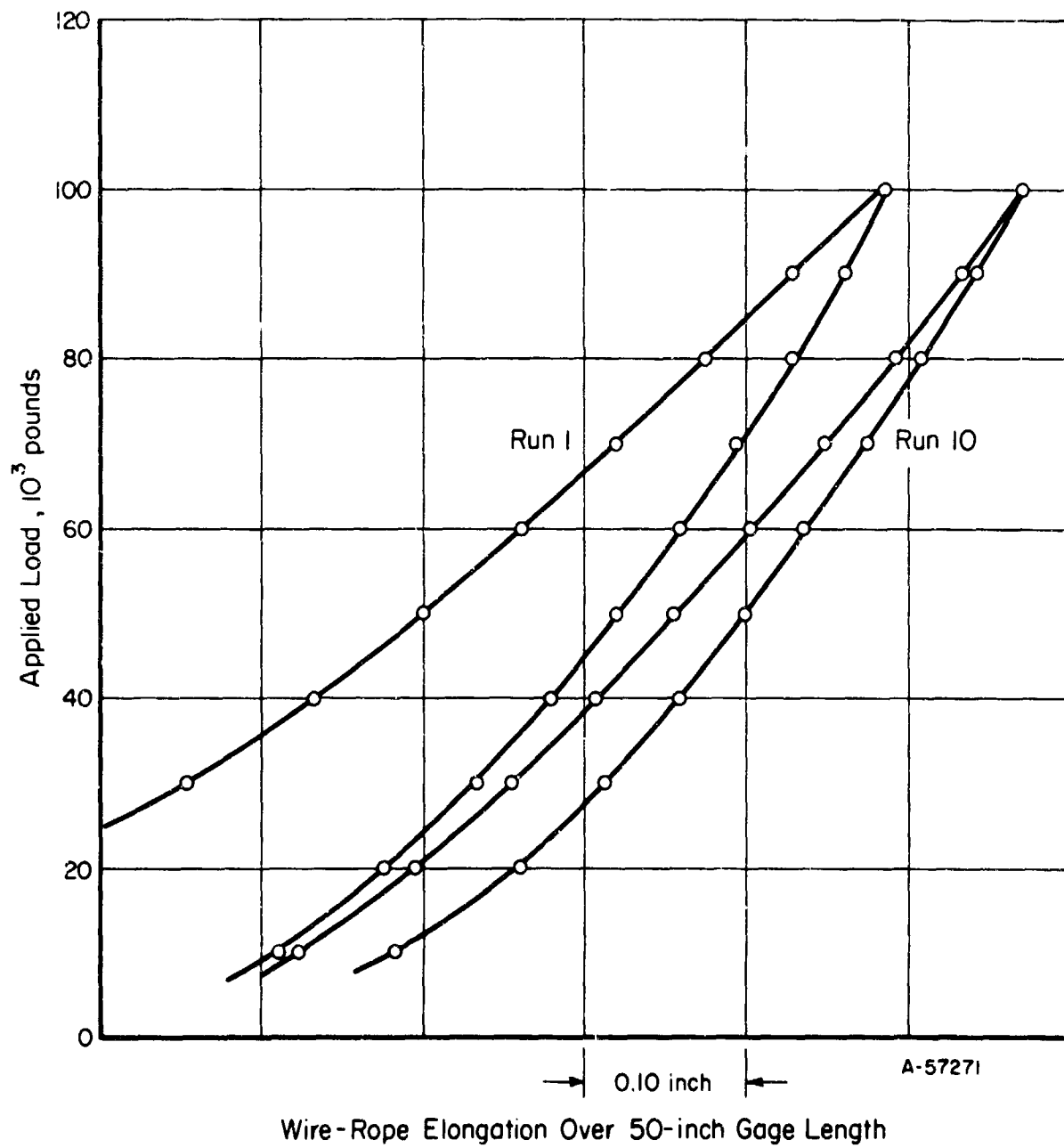


FIGURE D-10. LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION F, SPECIMEN 1

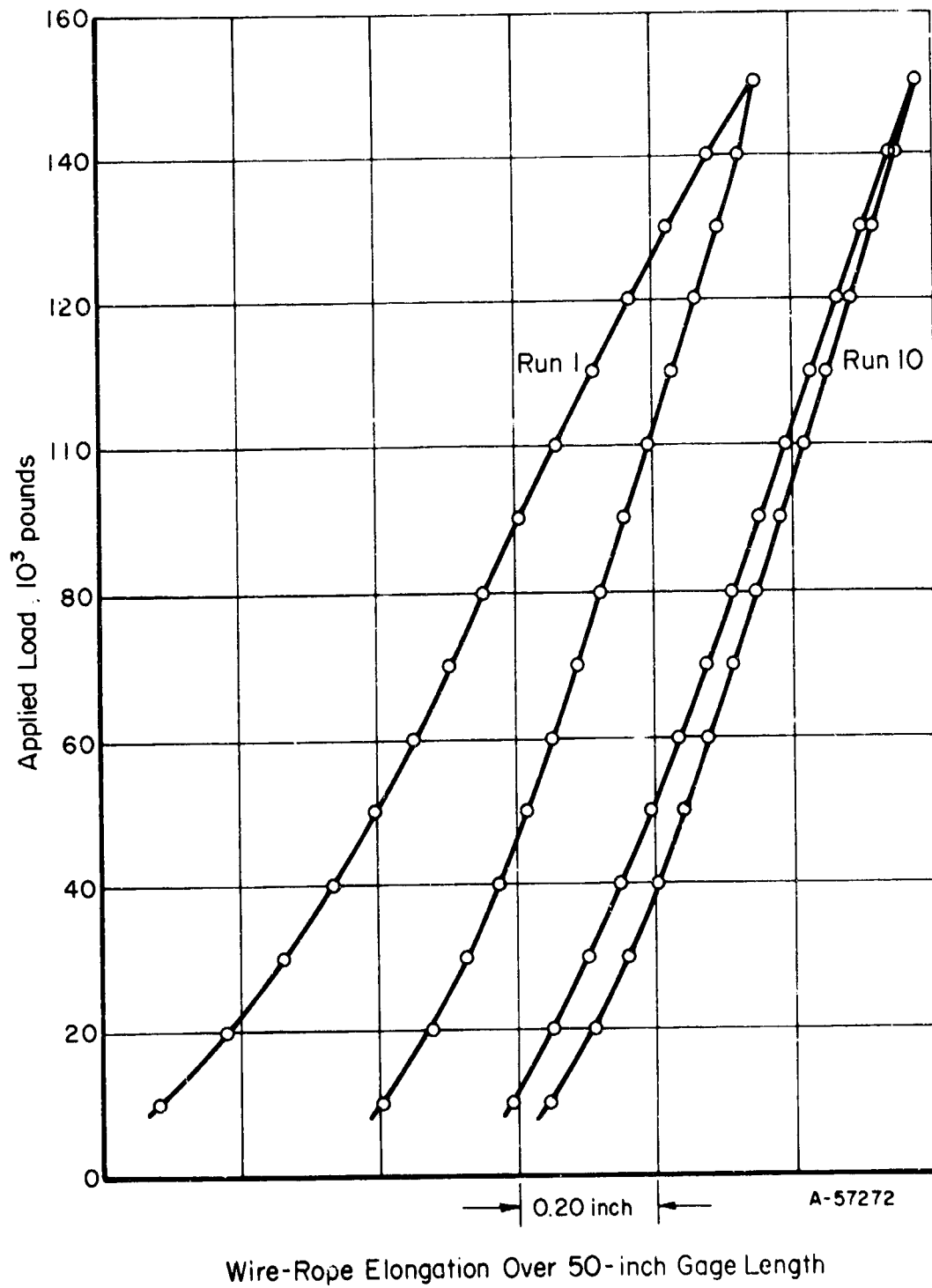


FIGURE D-11. LOAD-ELONGATION CURVES FOR WIRE-ROPE CONSTRUCTION F, SPECIMEN 2

APPENDIX E

MEASURED WIRE-ROPE CHARACTERISTICS

TABLE E-1. MEASURED WIRE-ROPE CHARACTERISTICS

	Wire-Rope Construction	Ultimate Strength, lb	Elastic Modulus, psi	Torque, ft-lb	Relative Flexibility
A.	6 x 30, Lang-lay, flattened strand	188,000 minimum (not measured)	14.5 x 10 ⁶	0.00203 T ^(b)	1.00
E.	6 x 10/12/Brangle	197,200/188,600 (a)	17.6 x 10 ⁶	0.00153 T	1.28
C.	6 x 8/12/Brangle	180,600(a)/182,800(a)	18.5 x 10 ⁶	0.00157 T	0.59
D.	6 x 7/Brangle	192,800/194,600	18.0 x 10 ⁶	0.00160 T	0.31
E.	6 x 36 Half-lock, flattened strand	210,000(a)/211,500 (a) 212,500 (a)/217,500	17.5 x 10 ⁶	0.00171 T	2.32
F.	6 x 31 Lang-lay, round strand	188,200 (a)/188,900 (a)	17.0 x 10 ⁶	0.00170 T	1.45

(a) Wire rope failed at socket.

(b) T = ten times load on wire rope, pounds.

E-1 and E-2

APPENDIX F

TRANSVERSE-IMPACT VELOCITIES

TABLE F-1. TRANSVERSE-IMPACT VELOCITIES

Weight of Impacting Body: 23 pounds

Propellant: 325 grains of 4831 smokeless powder.
(A rifle primer and 16 grains of black
powder were used to initiate burning.)

Cannon Bore: 1.027 inches

Wire-Rope Construction	Shot 1, ft/sec	Shot 2, ft/sec	Shot 3, ft/sec	Shot 4, ft/sec
A	198	196	196	199
B	208	201	193	200
C	196	198	207	200
D	197	198	194	199
E	195	200	195	200
F	195	197	193	199

APPENDIX G

PHOTOGRAPHS OF WIRE-ROPE DAMAGE RESULTING
FROM TRANSVERSE-IMPACT TESTS



(C)



(B)



(A)

FIGURE G-1 IMPACT AREA OF ROPE CONSTRUCTIONS A, B, AND C

40551



FIGURE G-2. IMPACT KINK OF ROPE CONSTRUCTIONS A, B, AND C

40554



40557

FIGURE G-3. IMPACT AREA OF ROPE CONSTRUCTIONS D, E, AND F



40552

FIGURE G-4. IMPACT KINK OF ROPE CONSTRUCTIONS D, E, AND F

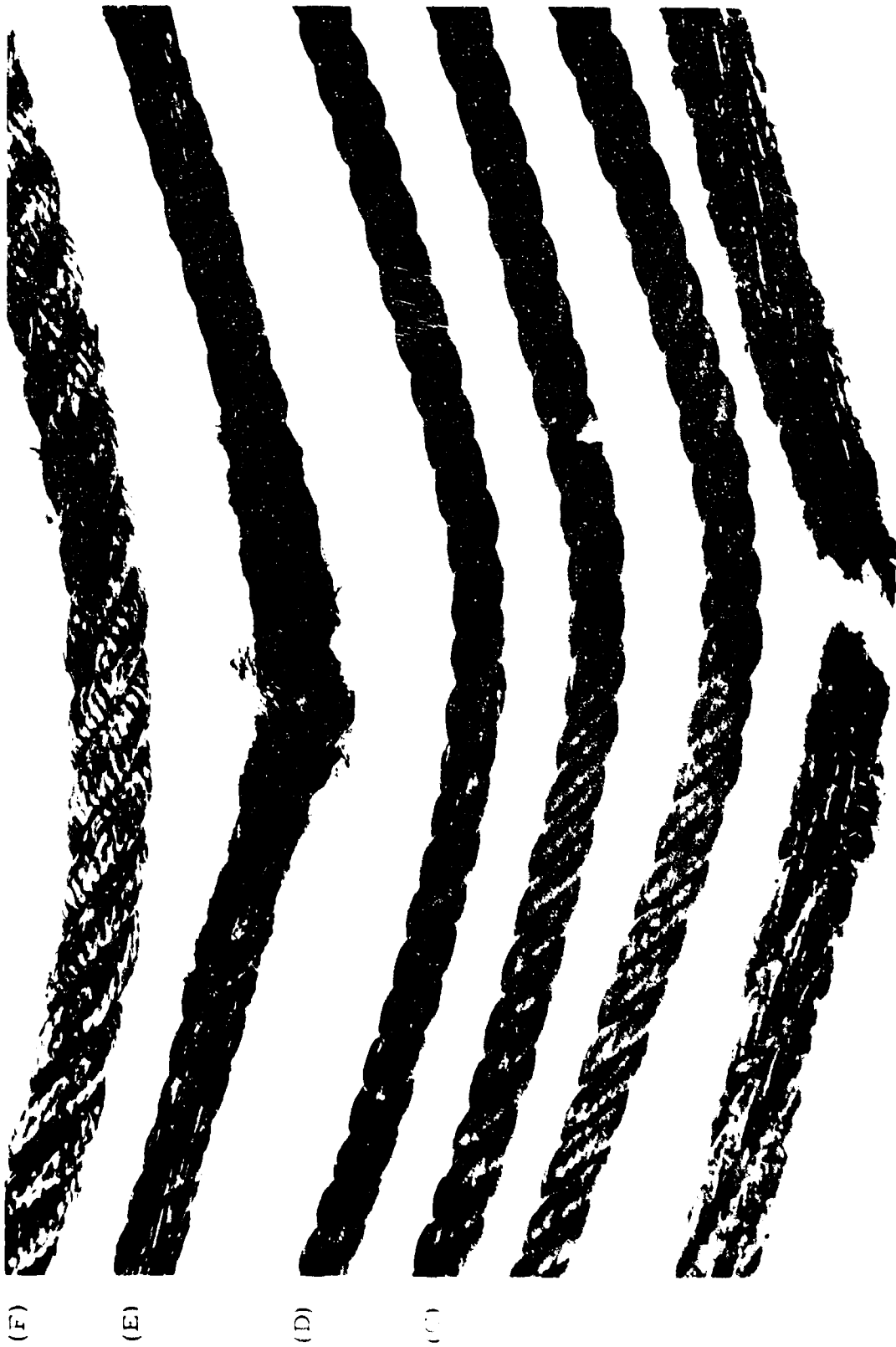


FIGURE G-5 ROPE-CORE DAMAGE DUE TO IMPACT TESTS

40555



40556

FIGURE G-6 IMPACT AREA OF STRANDS OF ROPE CONSTRUCTION A



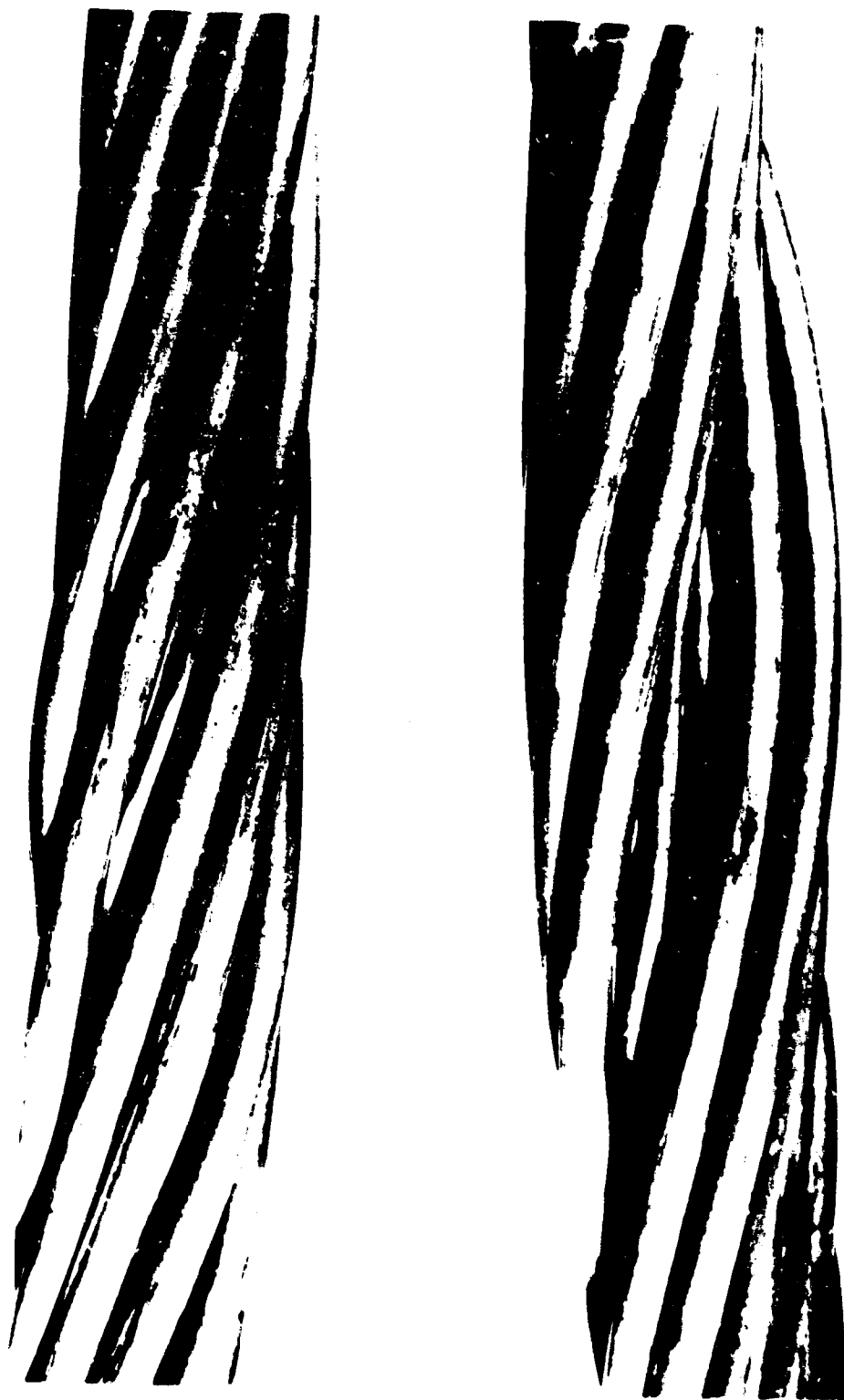
40565

FIGURE G-7 REVERSE SIDE OF STRANDS OF ROPE CONSTRUCTION A



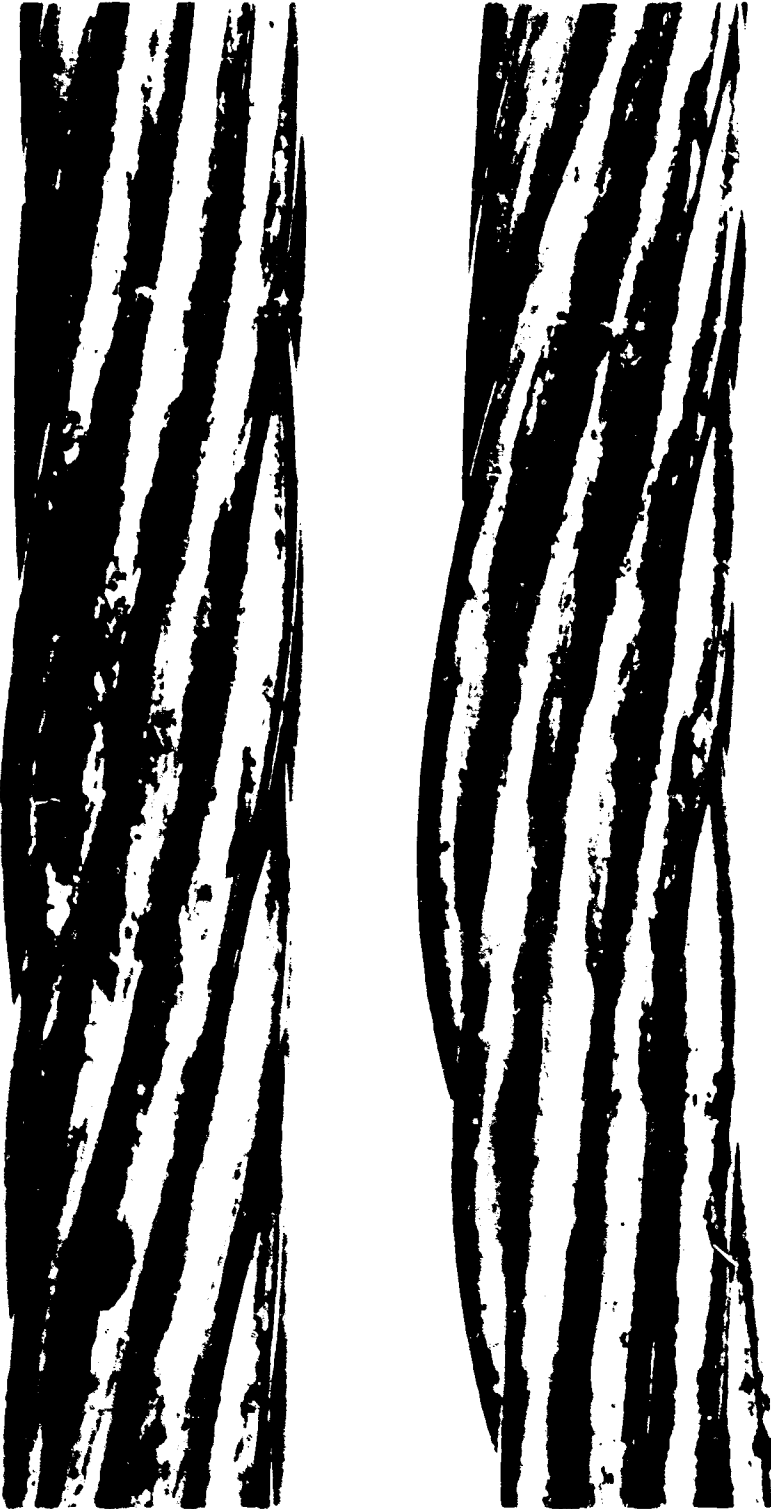
40560

FIGURE G-8. IMPACT AREA OF STRANDS OF ROPE CONSTRUCTION B



40554

FIGURE G-9 REVERSE SIDE OF STRANDS OF ROPE CONSTRUCTION B



40563

FIGURE C-10. IMPACT AREA OF STRANDS OF ROPE CONSTRUCTION C



40564

FIGURE G-11 REVERSE SIDE OF STRANDS OF ROPE CONSTRUCTION C



40567

FIGURE G-12 IMPACT AREA OF STRANDS OF ROPE CONSTRUCTION D



40558

FIGURE G-13 REVERSE SIDE OF STRANDS OF ROPE CONSTRUCTION D



40553

FIGURE G-14. IMPACT AREA OF STRANDS OF ROPE CONSTRUCTION E



40566

FIGURE G-15. REVERSE SIDE OF STRANDS OF ROPE CONSTRUCTION E



40561

FIGURE G-16. IMPACT AREA OF STRANDS OF ROPE CONSTRUCTION F



40562

FIGURE G-17 REVERSE SIDE OF STRANDS OF ROPE CONSTRUCTION F

APPENDIX H

RESULTS OF TRANSVERSE-IMPACT TESTS

H-1 and H-2

TABLE H-1. RESULTS OF TRANSVERSE-IMPACT TESTS

Wire-Rope Construction	Permanent Kink Angle	Major Dimension at Impact Point, in.	Minor Dimension at Impact Point, in.	Initial Rope Diameter, in.
A. 6 x 30, Lang-lay, flattened strand	15	1.615	1.292	1.420
B. 6 x 10/12/Brangle, Lang-lay, flattened strand	27	1.567	1.339	1.410
C. 6 x 8/12/Brangle, Lang-lay, flattened strand	22	1.592	1.267	1.388
D. 6 x 7/Brangle, Lang-lay, flattened strand	24	1.628	1.299	1.423
E. 6 x 36, half-lock, Lang-lay, flattened strand	13	1.678	1.336	1.453
F. 6 x 31, Lang-lay, round strand	12	1.582	1.351	1.410

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Battelle Memorial Institute - Columbus Laboratories 505 King Avenue Columbus, Ohio 43201		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP	
3. REPORT TITLE Validation of Design Theory for Aircraft Arresting-Gear Cable			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report covering work from May 5, 1965, to Dec. 4, 1967			
5. AUTHOR(S) (Last name, first name, initial) Gibson, Philip T., Alexander, Graham H., and Cress, Hobart A.			
6. REPORT DATE January 19, 1968		7a. TOTAL NO. OF PAGES 68	
		7b. NO. OF REFS 0	
8a. CONTRACT OR GRANT NO. NOW 65-0503		9a. ORIGINATOR'S REPORT NUMBER(S)	
A. PROJECT NO. G-7327-1		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
c.			
d.			
10. AVAILABILITY/LIMITATION NOTICES Distribution of this report is unlimited.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Naval Air Systems Command	
13. ABSTRACT <p>The work discussed in this report is the outgrowth of an earlier project entitled "Analytical Study of Aircraft Arresting-Gear Cable Design". The wire-rope design theory developed during this first study, together with information obtained from a number of wire-rope manufacturers, was used to select five different wire-rope constructions for evaluation as improved aircraft arresting cable. One of these ropes is an experimental construction designed at Battelle. Samples of these ropes were purchased for testing.</p> <p>The five wire ropes selected for evaluation included four flattened-strand and one round-strand construction. The standard rope design presently in use for deck pendants was used as a basis of comparison for all tests.</p> <p>These wire-rope constructions were subjected to a series of tests to establish their suitability for use as arresting cable. This report discusses the selection of the new rope designs and the results of the testing program.</p> <p>Tests on these wire ropes included evaluation of (1) ultimate strength, (2) elastic modulus, (3) torsion, (4) flexibility, and (5) resistance to damage by transverse impact.</p> <p>The tests of ultimate strength, elastic modulus, and torsion were conducted in the test laboratories of the rope manufacturers. Rope tension, torsion, and elongation were measured with instrumentation designed and built at Battelle.</p> <p>Tests of flexibility and resistance to transverse impact were conducted at Battelle. The transverse-impact tests required the design and construction of special apparatus utilizing an explosive-powered arresting hook. With this equipment, specimens of each wire-rope construction were impacted with the arresting hook at velocities equivalent to the landing speeds of aircraft on carriers. These impact tests proved to be the most satisfactory method of evaluating deck-pendant ropes in the laboratory.</p>			

Unclassified

Security Classification

14.	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	Wire rope Purchase cable Deck pendant Aircraft-arresting cable Cable Transverse-impact Failure modes Failure analysis Wire						

Unclassified
Security Classification